INTERACTIVE RESOURCE CENTER

TWELFTH EDITION

MECHANICAL AND ELECTRICAL EQUIPMENT FOR BUILDINGS

WALTER T. GRONDZIK · ALISON G. KWOK

WILEY

TWELFTH EDITION

Mechanical and Electrical Equipment for Buildings

How to get the most out of this book

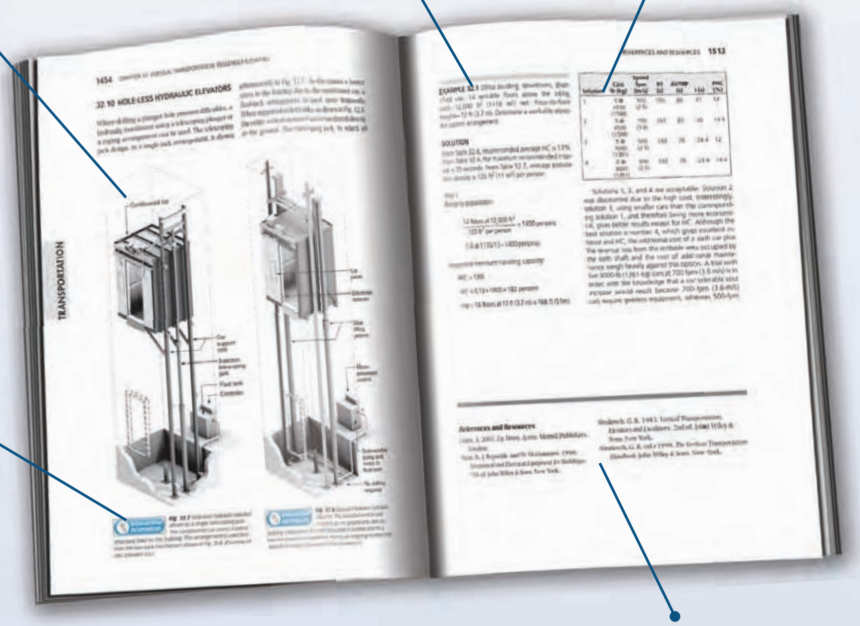
Maximize your study time with the tools and tips featured on the following pages. Using the integrated text and media within *Mechanical and Electrical Equipment for Buildings, Twelfth Edition* learning becomes an active process.

Example Problems with solutions help readers self-assess as they move through concepts

"Need to know" data on-hand in **Tables** throughout text

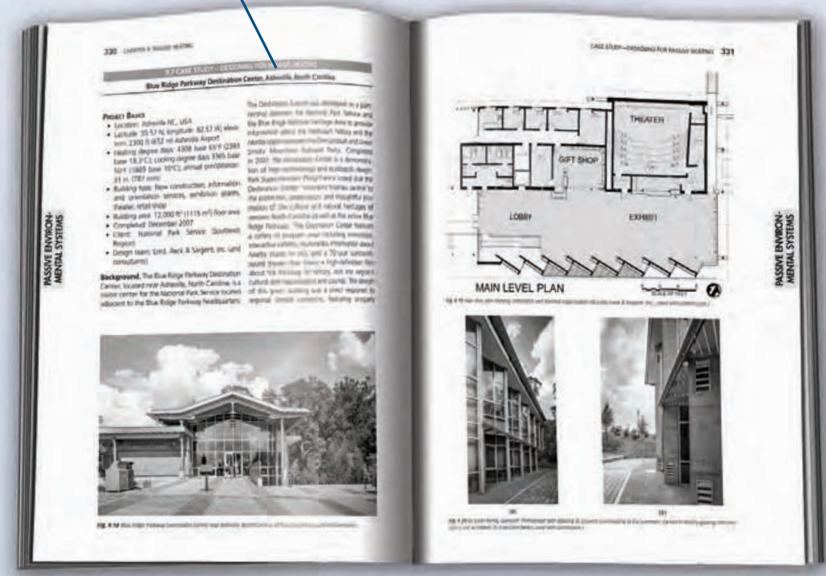
More than 2,200 **Illustrations,** with more than 300 new to this edition

Icons indicate availability of related interactive animations on the Interactive Resource Center companion site to expand learning on difficult concepts



Case Studies demonstrate successful integration of design strategies

End-of-Chapter References and Resources provide further learning on topics



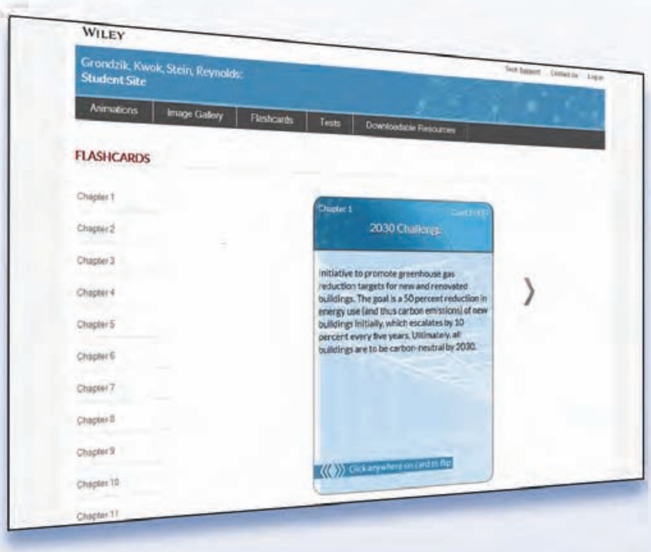
Appendices provide extensive reference and ancillary data without interrupting the flow of the main text

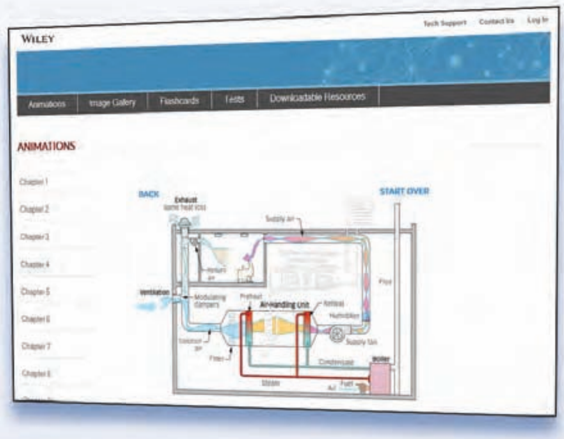
Additional Format Options

- Available in eBook formats for iOS, Android, Mac and PC, and all other eReaders and tablets
- Special package contains both Wiley E-Text version of full text and access to Interactive Resource Center (ISBN 978-1-118-99992-9)
- Available in Wiley CustomSelect www.wiley.com/college/custom

Interactive Resource Center

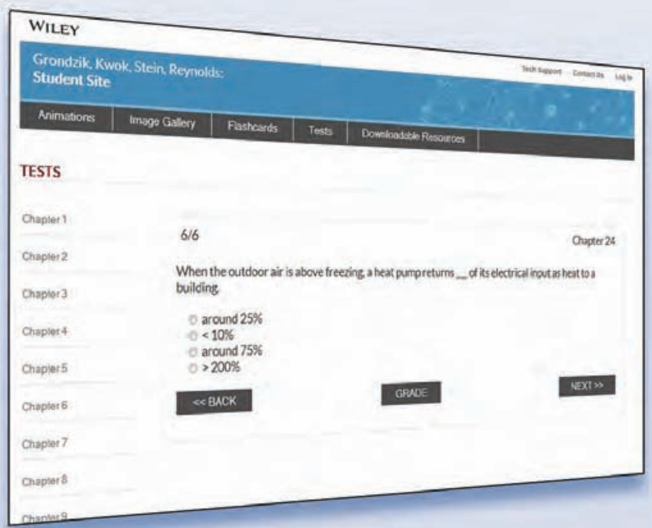
wiley.com/go/meeb12e (access code on inside front cover)





Over 500 **Interactive Flashcards** with images for mastering key concepts

Over 30 **Interactive Animations** walk learners through complex design processes



Interactive Self-Tests by chapter aid in assessment of key concepts

Full color **Case Studies** provide real world design examples and best practices

To purchase standalone access to the Interactive Resource Center student companion site please go to **wiley.com/go/meeb12e**

A registration code to access the resources included on the Interactive Resource Center is included with every new, print copy of *Mechanical and Electrical Equipment for Buildings, Twelfth Edition*. If you wish to purchase access to the Interactive Resource Center, you can go to www.wiley.com/go/meeb12e, click on "Student Companion Website" and then "Register," which will allow you to enter a code or to purchase access if you do not have a code. If you've purchased an e-Book version of this title please contact our Customer Care Department:

Customer Care Center - Consumer Accounts
10475 Crosspoint Blvd.
Indianapolis, IN 46256
Phone: (877) 762-2974
Fax: (800) 597-3299
Web: http://support.wiley.com

TWELFTH EDITION

Mechanical and Electrical Equipment for Buildings

Walter T. Grondzik
Architectural Engineer
Ball State University

Alison G. Kwok
Professor of Architecture
University of Oregon

WILEY

Cover image: The Hive Library, Worcester, Entrance Steps © Greg Newton/Arcaid/Corbis;
Illustration of the Hive Library © Max Fordham LLP and Feilden Clegg Bradley Studios
Cover design: C. Wallace

Part opener pages are from the drawing set for the Lillis Business Complex at the University of Oregon, designed by SRG Partnership, Portland, OR.

DISCLAIMER
The information in this book has been derived and extracted from a multitude of sources including building codes, fire codes, industry codes and standards, manufacturer's literature, engineering reference works, and personal professional experience. It is presented in good faith. Although the authors and the publisher have made every reasonable effort to make the information presented accurate and authoritative, they do not warrant, and assume no liability for, its accuracy or completeness or fitness for any specific purpose. The information is intended primarily as a learning and teaching aid, and not as a final source of information for the design of building systems by design professionals. It is the responsibility of users to apply their professional knowledge in the application of the information presented in this book, and to consult original sources for current and detailed information as needed, for actual design situations.

This book is printed on acid-free paper. ♾

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Grondzik, Walter T., author.
Mechanical and electrical equipment for buildings / Walter T. Grondzik, Architectural Engineer, Ball State University; Alison G. Kwok, Professor of Architecture, University of Oregon. — 12E.
pages cm
Includes index.
ISBN 978-1-118-61590-4 (cloth); 978-1-118-86228-5 (ebk.); 978-1-118-86718-1 (ebk.)
1. Buildings—Mechanical equipment. 2. Buildings—Electric equipment. 3. Buildings—Environmental engineering. I. Kwok, Alison G., author. II. Title.
TH6010.S74 2014
696—dc23 2013042724

10 9 8 7 6 5 4 3 2 1

Contents

PART VIII SIGNAL SYSTEMS 1407

PART IX TRANSPORTATION 1443

Preface

EIGHT DECADES AND A FEW GENERATIONS HAVE passed since the first edition of *Mechanical and Electrical Equipment for Buildings* was published in 1935. At its birth, this book was 429 pages long. Now, in the 12th edition, the book is more than 1800 pages, an increase of 400%. This expansion gives pause to our publisher and strengthens the arms of students—but, more seriously, it reflects the growing complexity of building design and the burgeoning knowledge base that confronts today's designers. Many new topics have been added over the years, and a few have disappeared; computer simulations are now routinely used in system design; equipment and distribution systems have undergone major changes; mechanical cooling has become commonplace; fuel choices have shifted (coal has moved from an on-site to an off-site energy source). In recent editions, the book has increasingly added discussions of "why" to its historic focus upon "how-to."

Most of the systems presented in this book consume energy and embody materials. Some systems consume water. As global society has moved from its early reliance on renewable energy sources (wind, water, and horse power) to today's seemingly unbreakable addiction to nonrenewable fossil fuels, it has also added vastly to its population and increased its per capita energy use. The resulting environmental degradation (primarily evident in air and water quality) has spurred efforts to reverse this decline. Governmental regulations are a part of such efforts, but this book emphasizes the investigation of alternative fuels and design approaches that go beyond those solutions currently deemed "acceptable" to society. Designers are encouraged to take an aggressive leadership role in mitigating environmental degradations.

On this note, it is becoming increasingly clear that climate change is well under way. The distressing value of 400 ppm of atmospheric CO_2 has been reached. We may not know the precise extent to which our insatiable carbon-based energy consumption is responsible for pushing the world to this new reality. However, it seems professionally irresponsible to believe that human actions have had no effect. It is very clear that the world's supply of fossil fuel is diminishing, that the consumption of these fuels dumps massive quantities of CO_2 into the air, and that there will be future consequences for all buildings (and their occupants) that today rely so thoroughly on nonrenewable energy sources.

The buildings of today contribute to negative global consequences that will impact future generations, and our approach to mechanical and electrical systems must consider how best to minimize and mitigate—if not negate—such negative environmental impacts. Thus, on-site resources—daylighting, passive solar heating, passive cooling, solar water heating, rainwater, wastewater treatment, photovoltaic electricity—share the spotlight with traditional off-site resources (natural gas, oil, the electrical grid, water and sewer lines). On-site processes can be area-intensive and labor-intensive and can involve increased first costs that require years to recover through savings in energy, water, and/or material consumption. Off-site processes are usually subsidized by society, often with substantial environmental costs that accrue to the commons. On-site energy use requires us to look beyond the building, to pay as much attention to a building's context as to the mechanical and electrical spaces, equipment, and systems within.

Throughout the many editions of this book, another trend has emerged. Society has slowly moved from systems that centralize the provision of heating, cooling, water, and electricity toward those that encourage more localized production and control. Increased sophistication of digital control systems has encouraged this trend. Further encouragement comes from multipurpose buildings whose schedules of occupancy are fragmented and from corporations with varying work schedules that result in partial occupancy on weekends. Another factor in this move to decentralization is worker satisfaction; there is increasingly solid evidence that productivity increases with a sense of individual control of one's work environment. Residences are commonly being used as office work environments. Expanding communications networks have made this possible. As residential designs thus become more complex (with office-quality lighting, zones for heating/cooling, sophisticated communications, noise control), our nonresidential work environments become more attractive and individual.

Air and water pollution problems stemming from buildings (and their systems and occupants) are widely recognized and generally condemned. A rapidly increasing interest in green design on the part of clients and designers may help to mitigate such problems, although green design is hopefully just an intermediate step in the journey to truly sustainable solutions. And no, we are not designing sustainable solutions today—despite the claims about sustainable this and sustainable that which fill the Internet, conference presentations, and professional journals.

Another pervasive pollutant affecting our quality of life is noise. Noise will impact building siting, space planning, exterior and interior material selections—even the choice of cooling systems (as with natural ventilation). Air and water pollution can result in physical illness, but so can noise pollution, along with its burden of mental stress.

This book is written primarily for the North American building design community and has always emphasized examples from this region. Yet other areas of the world, some with similar traditions and fuel sources, have worthy examples of new strategies for building design utilizing on-site energy and energy conservation. Thus, buildings from Europe and Asia appear in this 12th edition, along with many North American examples. Listings of such buildings (and associated researchers and designers) have been included in the index of this edition. Design standards presented in this book are generally reflective of practice in the United States; this is a result of our experiences, but also reflects a desire not to confuse readers by listing the many, many variations in design standards that exist across the globe,

Building system design is now widely undertaken using computers, often through proprietary software that includes hundreds of built-in assumptions. This book encourages the designer to take a rational approach to system design: to verify intuitive design moves and assumptions and to use computers as tools to facilitate such verification, but to use patterns and approximations to point early design efforts in the right direction (and catch the occasional garbage-in/garbage-out simulation result). Hand calculations have the added benefit of exposing all pertinent variables and assumptions to the designer. This in itself is a valuable rationale for conducting some portion of an analysis manually. Rough hand-calculated results should point in the same direction as results obtained with a computer; the greater the disparity, the greater the need to check both approaches. This is not to disparage the use of simulations, which are valuable (if not indispensable) in optimizing complex and sometimes counterintuitive systems.

This book is written with the student, the architect- or engineer-in-training, and the practicing professional in mind. Basic theory, preliminary design guidelines, and detailed design procedures allow the book to serve both as an introductory text for the student and as a more advanced reference for both professional and student. This work is intended to be used as a textbook for a range of courses in architecture, architectural engineering, and building/construction management.

A "MEEB 12" World Wide Web (WWW) site provides supporting materials to enhance learning about and understanding of the concepts, equipment, and systems dealt with in this book. The opportunity to provide color images via the Web is truly exciting. As with previous editions, a 12th edition Instructor's Manual has been developed to provide additional support for those teaching with the book. The manual, updated by Troy Peters (with input from Walter Grondzik and Alison Kwok), outlines the contents and terminology in each chapter; highlights concepts of special interest or difficulty; and provides sample discussion, quiz, and exam questions. The manual is available to instructors who have adopted this book for their courses.

Mechanical and Electrical Equipment for Buildings continues to serve as a reference for architectural registration examinees in the United States and Canada. We also hope to have provided a useful reference book for the offices of architects, engineers, and building managers.

Walter T. Grondzik
Alison G. Kwok

Visit **www.wiley.com/go/meeb12e**
for the expanding set of learning resources that accompany this book.

Acknowledgments

Many people and organizations have contributed knowledge, materials, and insights to the several editions of this book. We begin this acknowledgment with those from whose work we have borrowed at length: J. Douglas Balcomb, Baruch Givoni, John Tillman Lyle, Murray Milne, William McGuinness, and Victor Olgyay; ASHRAE (the American Society of Heating, Refrigerating and Air-Conditioning Engineers), the American Solar Energy Society (ASES), the Illuminating Engineering Society of North America (IESNA), the National Drinking Water Clearinghouse, the National Small Flows Clearinghouse, the National Fire Protection Association (NFPA); and the many equipment manufacturers whose product information and photographs are used to illustrate the book.

The twelfth edition of *Mechanical and Electrical Equipment for Buildings* (MEEB) is the first edition in decades to not be published under the names of long-term authors Benjamin Stein and John Reynolds. We—and you the reader—owe a great debt to the insight and technical knowledge complied into MEEB over the many years during which Stein and Reynolds were sole authors of this book. This knowledge remained in place as they transitioned out of roles as primary authors, and provides the core around which this edition was developed.

Numerous professionals provided valuable assistance in assembling materials, and clarifying ideas and details. These include Michael Utzinger and Joel Krueger (Aldo Leopold Legacy Center), Vikram Sami and Jim Nicolow (Blue Ridge Parkway Destination Center), Craig Christiansen (NREL research reports), William Lowry (climate of cities), Daniel Panetta (AIWPS and recycling at California Polytechnic, San Luis Obispo), Dr. Jonathan Stein (computer applications), John A. Van Deusen (vertical transportation), and Martin Yoklic (cooltower performance analysis). In addition, Peter Clegg (Feilden Clegg Bradley Studios); Guy Nevill and Max Fordham (The Hive); Robert Schnare and THA (Mercy Corps); Bergsund DeLaney Architecture and Planning; Nora Cronin, St. Vincent dePaul of Lane County (Stellar Apartments); Skylar Swinford (Glasswood); Ron Rochon and Jim Hanford of Miller Hull Partnership; Denis Hayes, Bullitt Foundation (Bullitt Center); Julia Lau and David Lung (International Commerce Centre); and Adam Cohen (CEED) contributed to several case studies that are new to this edition. Donald Corner, Lee Eckert, Tisha Egashira, Bruce Haglund, Toshi Woudenberg, Erica Ling, and Thomas Collins kindly contributed images that enhance the book.

In addition to drawings by Michael Cockram (whose work first appeared in the eighth edition), we are very pleased to include in this twelfth edition illustrations by Zeta Fernando, Tyler Mavichien, Wesley Thompson, Karen Tse, and Ayush Vaidya. We continue to thank those who assisted with illustrations for the 11th edition: Lisa Leal, Nathan Majeski, and Jonathan Meendering; and the 10th edition: Dain Carlson, Amanda Jo Clegg, Eric Drew, Erik Winter, and (again) Jonathan Meendering. These are former students (now professionals) who embraced the principles and concepts of environmental technology in their design work and therefore clearly understood what they were drawing. We also acknowledge the many architects and engineers who provided illustrations of their buildings and design artifacts that appear in many of the chapters—citations to these firms and individuals are found throughout the book.

Student users turn out to be a particularly valuable audience through which to find needed improvements in any textbook. Students at the University of Oregon have, over many years, raised probing questions whose answers have resulted in changes to following editions. Valuable suggestions have come from many graduate teaching fellows at the University of Oregon, particularly Rachel Auerbach, David Bartley, Mike Beamer, David Bisers, Christina Bollo, Gabriel Brown, Thomas Collins, Christopher Deel, Charlie Deese, Mathieu Deraspe, Sophia Duluk, Alfredo Fernandez-Gonzalez, Erin Fox, Sara Goenner, Jeff Guggenheim, Susie Harriman, Diana Hogard, Eric Issertes-Carbonnier, Jake Keeler, Anna Liu, Angela Matt, Jonathan Meendering, Heather Nelson, Christopher Nielson, Tobin Newburgh, Roger Ota, Therese Peffer, Troy Peters, David Posada, Barbara Reed, Amanda Rhodes, Nick Rajkovich, Ted Shriro, Jonathan Thwaites, Nick Venezia, Michael Walsh, and Paul Wolf. Former Oregon students who helped with research include Troy Anderson, Daniel Irurah, Reza Javandel, Jeff Joslin, and Emily Wright. Michael Ober provided unrestrained encouragement with his video extolling the virtues of "MEEB" (check it out on YouTube).

Much of the work involved in producing a manuscript is accomplished by dedicated supporting personnel. We are truly grateful to: Ayush Vaidya (long hours of file coordination, updates, project management, flashcard development, dumpling mastery), Karen Tse (images, permissions, file management, chocolate mastery), Tyler Mavichien (images, permissions, file management, blueberry mastery), Cem Kayatekin (case study development, editing and heavy lifting, grammar mastery), and Collin Janke (case study development and medical mastery); Sara Tepfer (calculations, case study development, Milano mastery), Alisa Kwok (updates, database, and spice mastery), Leora Tanjuatco (chapter reviews), and Zeta Fernando (drawings). Thanks also to Troy Peters for updating the companion materials for instructors and students. Special, and very sincere, thanks go to Theodore J. Kwok, who provided extensive and prompt input on database development and troubleshooting (again) for this edition.

Finally, we are indebted to the staff at John Wiley & Sons for their diligent and highly professional work, especially Amanda Miller, vice president and publisher; Paul Drougas, acquisitions editor; Lauren Olesky, developmental editor; Terrence Broiles, animations; Michael New, editorial assistant, Amy Odum, production editor; Devra Kunin of Foxxe Editorial Services, copyeditor, and Aptara Corp., compositors. The cover design was developed by C. Wallace.

P A R T I

THE BUILDING DESIGN CONTEXT

The design of mechanical and electrical equipment for buildings is often not considered until many other important design decisions have already been made. This is sometimes a result of a relay-race type of design process, whereby decisions are handed off sequentially from architect to consulting engineer. In many cases, such equipment (constituting active systems) is considered to have a corrective function, permitting a building design to work on a site and in a climate that were essentially ignored. Such is the power of fossil-fueled systems; however, such power comes with a price—both economic and environmental.

The chapters that compose Part I are intended to encourage designers to use the wonderfully flexible building design process to full advantage, and to include site and climate—as well as the key objectives of thermal and visual comfort and indoor air quality—in their earliest design thinking. Chapter 1 discusses the building design process and the roles played by codes, costs, and owner's project requirements in shaping a final building design. The critical importance of clear design intents and criteria is emphasized. Principles to guide environmentally responsible design are given. Chapter 2 discusses the relationship of energy, water, and material resources to buildings, from design through demolition. The concept of environmental footprint is introduced as an ultimate arbiter of design decision making. Chapter 3 encourages designers to view a building site as a collection of renewable resources, to be used as appropriate in the lighting, heating, and cooling of buildings.

CHAPTER 1

Design Process

IN MARCH 1971 VISIONARY ARCHITECT MALCOLM WELLS published a watershed article in *Progressive Architecture.* It was rather intriguingly and challengingly titled "The Absolutely Constant Incontestably Stable Architectural Value Scale." In essence, Wells argued that buildings should be *benchmarked* (to use a current term) against the environmentally regenerative capabilities of wilderness (Fig. 1.1). This seemed a radical idea then—and remains so even now, over 40 years later. Such a set of values, however, may be just what is called for as the design professions slowly but inevitably move from *energy-efficient* to *green* to *sustainable* design in the coming decades. The main problem with Wells's "Incontestably Stable" benchmark is that most buildings fare poorly (if not dismally) against the environment-enhancing characteristics of wilderness. But perhaps this is more of a wakeup call than a problem.

As we sit firmly in the first quarter of the twenty-first century, *Progressive Architecture* is no longer in business, Malcolm Wells has sadly passed away, mechanical and electrical equipment has improved, simulation techniques have radically advanced, and information exchange has been revolutionized. In broad terms, however, the design process has changed little since the early 1970s. This should not be unexpected, as the design process

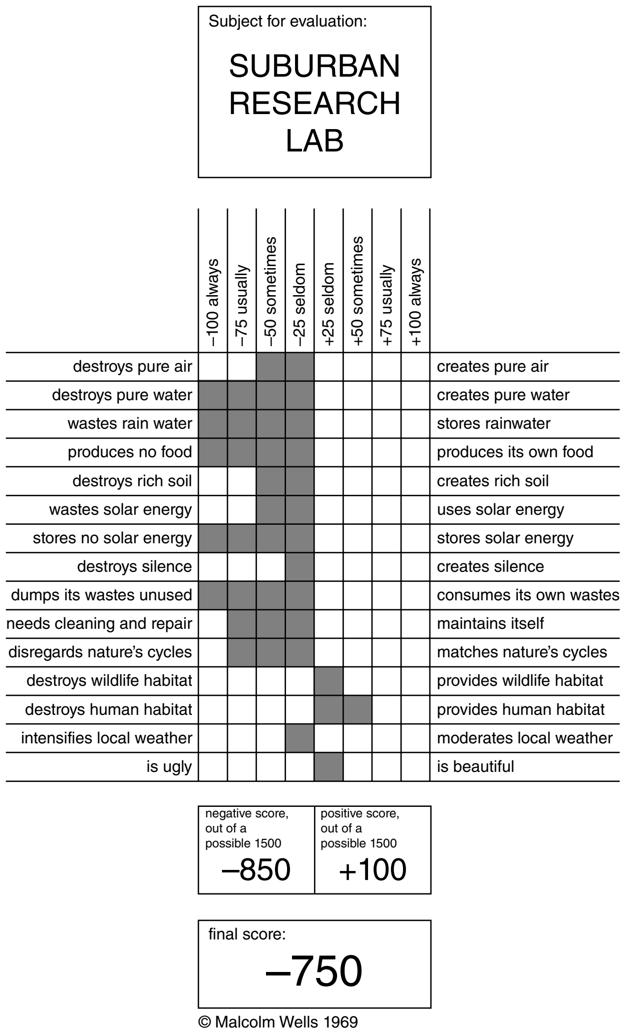


Fig. 1.1 *Evaluation of a typical project using Malcolm Wells's "absolutely constant incontestably stable architectural value scale." The value focus was wilderness; today it might well be sustainability. (© Malcolm Wells. Used with permission from Malcolm Wells. 1981.* Gentle Architecture. *McGraw-Hill. New York.)*

is simply a conceptual structure within which to develop a solution to a problem. The values and philosophy that underlie the design process absolutely must change, however, in the coming decades (if not immediately). The beauty of Wells's rather simple scale was its crystal-clear focus upon the values that accompanied his design solutions—and the explicit stating of those values. To meet the challenges of the coming decades, it is critical that designers consider and adopt values appropriate to the nature of the problems being confronted—both at the individual project scale and globally. Nothing less makes sense.

1.1 INTRODUCTION

The design process is an integral part of the larger and more complex building procurement process through which an owner defines facility needs, considers architectural possibilities, contracts for design and construction services, and uses the resulting facility. Numerous decisions (literally thousands) made during the design process will determine the need for specific mechanical and electrical systems and equipment, and very often will determine eventual owner and occupant satisfaction. Discussing selected aspects of the design process seems a good way to start this book.

A building project typically begins with predesign activities that establish the need for, feasibility of, and proposed scope for a facility. If a project is deemed feasible and can be funded, a multiphase design process follows. The design phases are typically described as conceptual design, schematic design, and design development. If a project remains feasible as it progresses, the design process is followed by the construction and occupancy phases. In fast-track approaches (such as design-build), design efforts and construction activities may substantially overlap.

Predesign activities may be conducted by the design team (often under a separate contract), by the owner, or by a specialized consultant. The product of predesign activities should be a clearly defined scope of work for the design team to act upon. This product is variously called a *program*, a *project brief*, or the *owner's project requirements*. The design process converts this statement of the owner's requirements into drawings and specifications that permit a contractor to then convert the owner's (and designer's) wishes into a physical reality.

The various design phases are the primary areas of concern to the design team. The design process may span weeks (for a simple building or system) or years (for a large, complex project). The design team may consist of a sole practitioner for a residential project or 100 or more people located in different offices, cities, or even countries for a large project. Decisions made during the design process, especially during the early stages, will affect the project owner and occupants for many years—influencing operating costs, maintenance needs, comfort, enjoyment, and productivity.

The scope of work accomplished during each of the various design phases varies from firm to firm and project to project. In many cases, explicit expectations for the phases are described in professional service contracts between the design team and the owner. A series of images illustrating the development of the Solar Living Center and the Real Goods Store (starting with Figs. 1.2 and 1.3)

Fig. 1.2 *The Solar Living Center and Real Goods Store, Hopland, California; exterior view. (Photo © Bruce Haglund; used with permission.)*

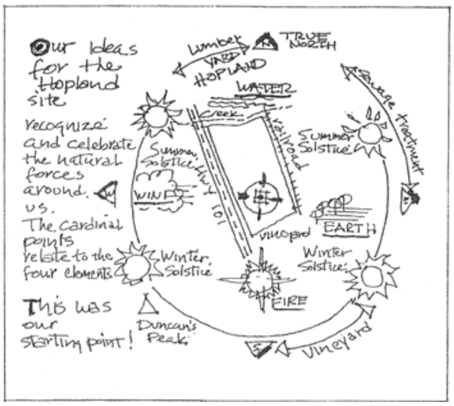


Fig. 1.3 *Initial concept sketch for the Solar Living Center and Real Goods Store, a site analysis. (Drawing by Sim Van der Ryn; reprinted from* A Place in the Sun *with permission of Real Goods Trading Corporation.)*

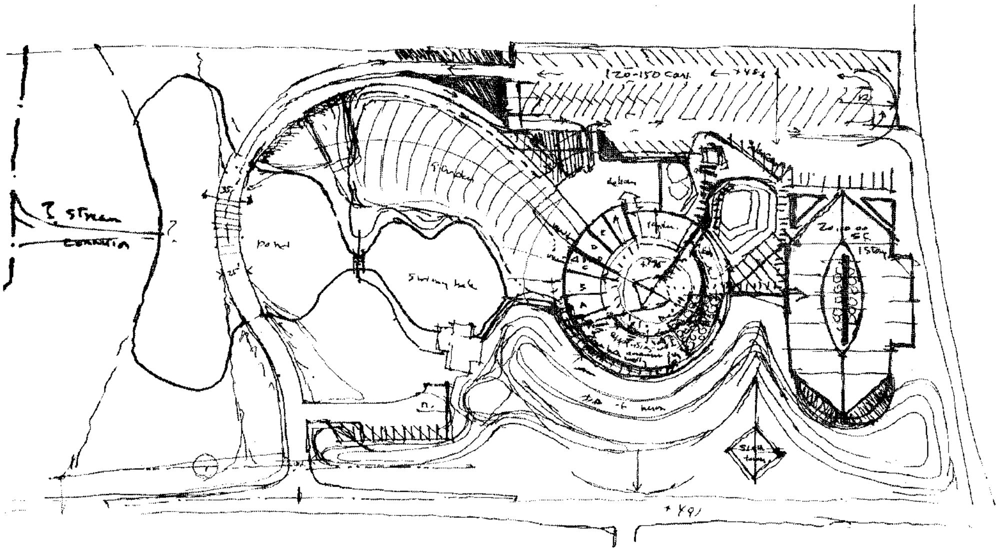


Fig. 1.4 *Conceptual design proposal for the Real Goods Solar Living Center. The general direction of design efforts is suggested in fairly strong terms (the "first, best moves" for design direction), yet details are left to be developed in later design phases. There is a clear focus on rich site development even at this stage—a focus that was carried throughout the project. (Drawing by Sim Van der Ryn; reprinted from* A Place in the Sun *with permission of Real Goods Trading Corporation.)*

is used to illustrate the various phases of a building project. (The story of this remarkable project, and its design process, is chronicled in Schaeffer et al., 1997.) Broadly, the purpose of conceptual design (Fig. 1.4) is to outline a general solution to the owner's program that meets the budget and captures the owner's imagination so that design can continue. All fundamental decisions about the proposed building should be made during conceptual design (not that things can't or won't change). During schematic design (Figs. 1.5 and 1.6), the conceptual solution is further developed and refined.

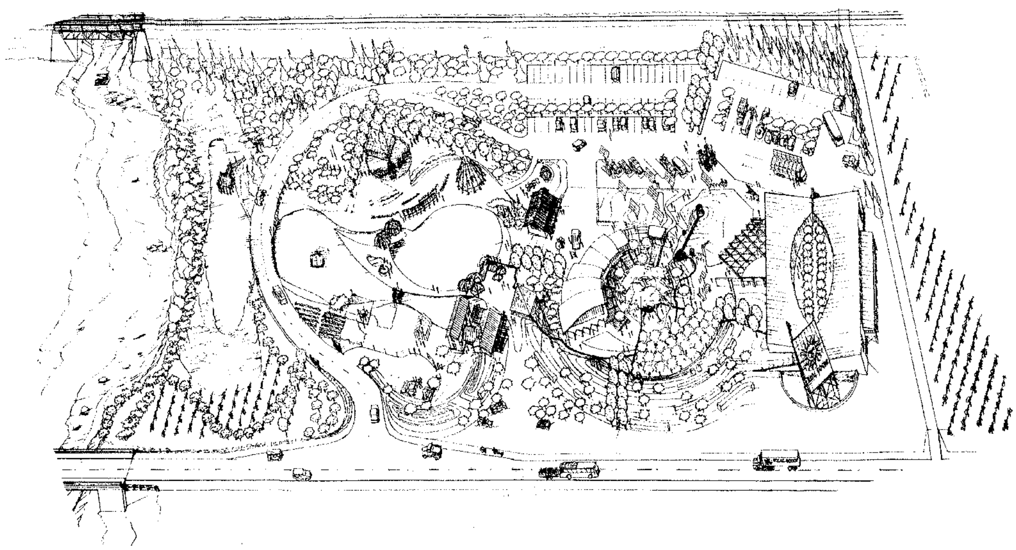


Fig. 1.5 *Schematic design proposal for the Solar Living Center and Real Goods Store. As design thinking and analysis evolve, so does the specificity of a proposed design. Compare the level of detail provided at this phase with that shown in Fig. 1.4. Site development has progressed, and the building elements begin to take shape. The essence of the final solution is pretty well locked into place. (Drawing by David Arkin; reprinted from* A Place in the Sun *with permission of Real Goods Trading Corporation.)*

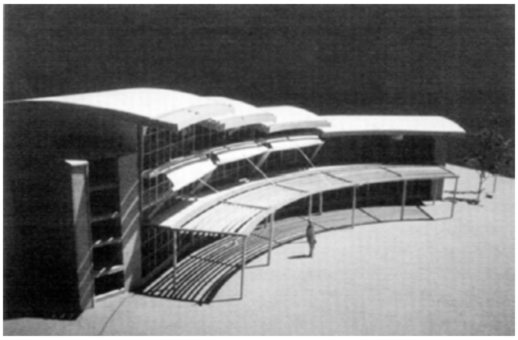


Fig. 1.6 *Scale model analysis of shading devices for the Solar Living Center and the Real Goods Store. This is the sort of detailed analysis that would likely occur during schematic design. (Photo, model, and analysis by Adam Jackaway; reprinted from* A Place in the Sun *with permission of Real Goods Trading Corporation.)*

During design development (Fig. 1.7), all decisions regarding a design solution are finalized, and construction drawings and specifications detailing those innumerable decisions are prepared.

The construction phase (Fig. 1.8) is primarily in the hands of the contractor, although design decisions have determined what will be built and may dramatically affect constructability. The building owner and occupants are the key players during the occupancy phase (Fig. 1.9). Their experiences with the building will clearly be influenced by design decisions and construction quality, as well as by maintenance and operation practices. A feedback loop that allows construction and occupancy experiences (lessons learned—both good and bad)

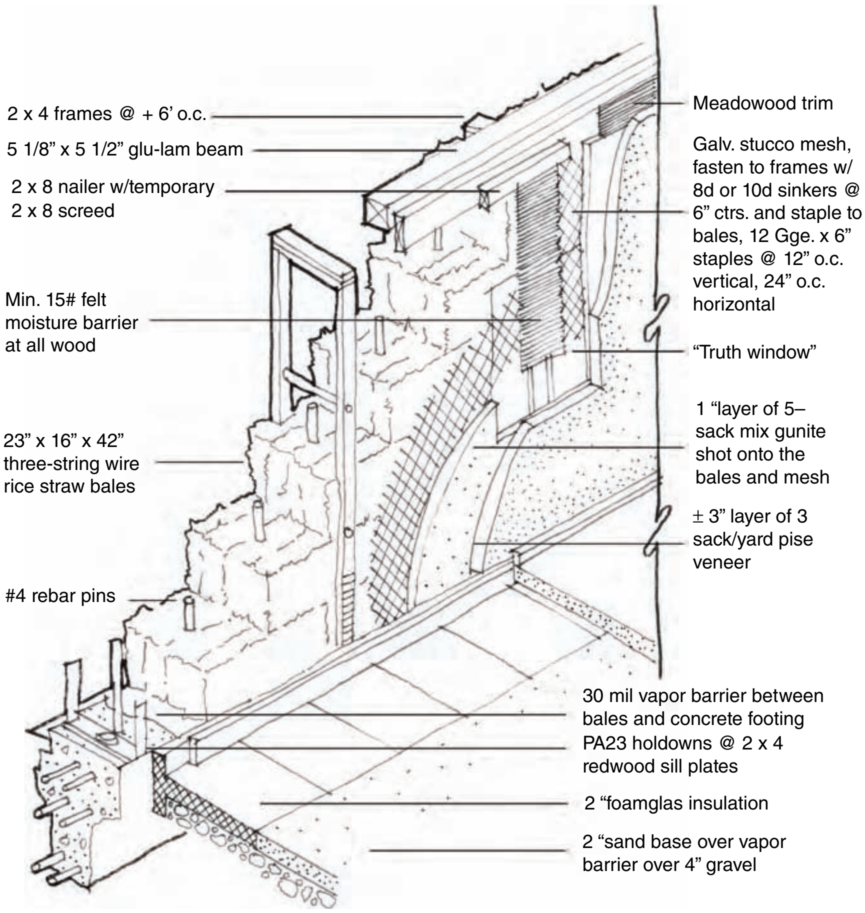


Fig. 1.7 *During design development, the details that convert an idea into a building evolve. This drawing illustrates the development of working details for the straw bale wall system used in the Solar Living Center and the Real Goods Store. Material usage and dimensions are refined and necessary design analyses (thermal, structural, economic) completed. (Original drawing by David Arkin; reprinted from* A Place in the Sun *with permission of Real Goods Trading Corporation. Redrawn by Erik Winter.)*

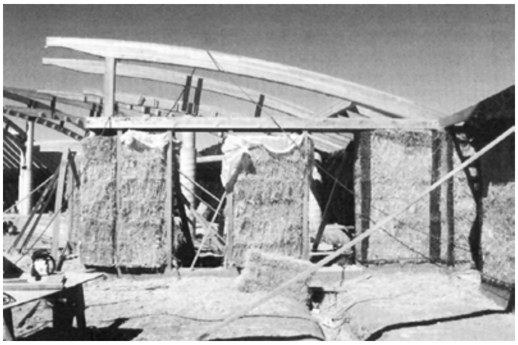


Fig. 1.8 Construction phase photo of the straw bale walls of the Solar Living Center and Real Goods Store. Design intent becomes reality during this phase. (Reprinted from A Place in the Sun *with permission of Real Goods Trading Corporation.)*

to be used by the design team on future projects is essential to good design practice.

1.2 DESIGN INTENT

Design efforts should focus upon achieving a solution that will meet the expectations of a well-thought-out and explicitly defined design intent. A design intent is simply a statement that outlines an expected high-level outcome of the design process. Making such a fundamental statement is critical to the success of a design, as it points to the general direction(s) that the design process must take to achieve success. Design intent should not try to capture the totality of a building's character; this will come only with the completion of the

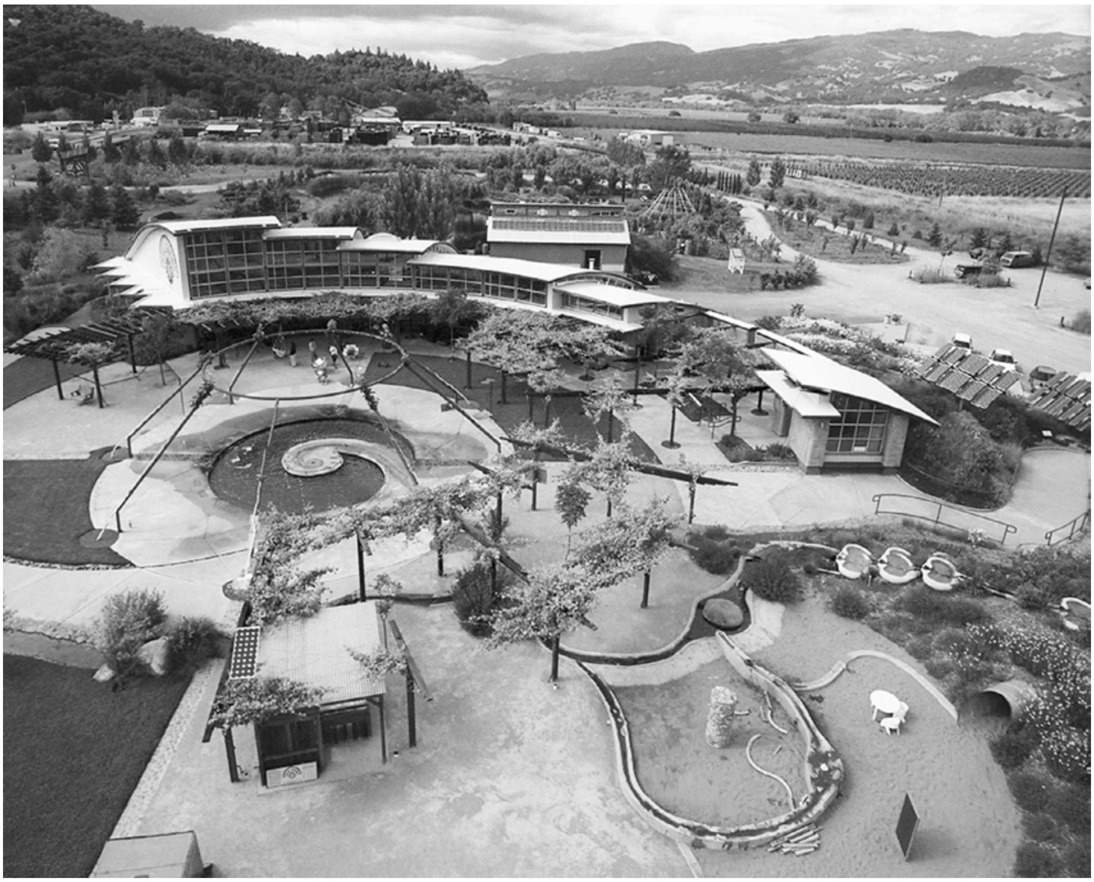


Fig. 1.9 The Solar Living Center and Real Goods Store during its occupancy and operations phase. Formal and informal evaluation of the success of the design solution may (and should) occur. Lessons learned from these evaluations can inform future projects. This photo was taken during a Vital Signs case study training session held at the Solar Living Center. (© Cris Benton, kite aerial photographer and professor, University of California–Berkeley; used with permission.)

design. It should, however, adequately express the defining characteristics of a proposed building solution. Example design intents (from among thousands of possibilities) might include the following:

- The building will provide outstanding comfort for its occupants.
- The design will consider the latest in information technology.
- The building will be green, with a focus on indoor environmental quality.
- The building will be carbon neutral.
- The building will provide a high degree of flexibility for its occupants.

Clear design intents are important because they set the tone for design efforts, allow all members of the design team to understand what is truly critical to success, provide a general direction for early design efforts, and put key or unusual design concerns on the table. Professor Larry Peterson, former director of the Florida Sustainable Communities Center, has described the earliest decisions in the design process as an attempt to make the "first, best moves." Strong design intent will inform such moves. Weak intent will result in a weak building. Great moves too late will be futile. The specificity of the design intent will evolve throughout the design process. *Outstanding comfort* during conceptual design may become *outstanding thermal, visual, and acoustic comfort* during schematic design.

1.3 DESIGN CRITERIA

Design criteria are the benchmarks against which success or failure in meeting design intent is measured. In addition to providing a basis against which to evaluate success, design criteria will ensure that all involved parties seriously address the technical and philosophical issues underlying a project's design intent. Setting design criteria demands the clarification and definition of many intentionally broad terms used when crafting design intent statements. For example, what is really meant by *green*, by *flexibility*, by *comfort*? If such terms cannot be benchmarked, then there is no way for the success of a design to be evaluated—essentially anything goes, and all solutions are potentially equally valid. Setting design criteria for qualitative issues (such as *exciting*, *relaxing*, or *spacious*) can be especially challenging, but equally important (and possible). Design criteria should be established as early in the design process as possible—but certainly no later than the schematic design phase. Because design criteria will define success or failure in a specific area of the building design process, they should be realistic and not subject to whimsical change. In many cases, design criteria will be used both to evaluate the success of a design approach or strategy and to evaluate the performance of a system or component in a completed building. Examples of design criteria might include the following:

- Thermal conditions will meet the requirements of ASHRAE Standard 55.
- The power density of the lighting system will be no greater than 0.7 W/ft^2.
- The building will achieve a LEED® Silver certification.
- Fifty percent of building water consumption will be provided by rainwater capture.
- Background sound pressure levels in classrooms will not exceed RC 35.

1.4 METHODS AND TOOLS

Methods and tools are the means through which design intent is accomplished. They include design methods and tools, such as a heat loss calculation procedure or a sun angle calculator. They also include the components, equipment, and systems that collectively define a building. It is important that an appropriate method or tool be used for a particular purpose. It is also critical that methods and tools (as means to an end) never be confused with either design intent (a desired end) or design criteria (benchmarks for success).

For any given design situation, there are typically many valid and viable solutions available to the design team. It is important that no reasonable solution be overlooked or ruled out as a result of design process short circuits. Although this may seem unlikely, methods (such as fire sprinklers, electric lighting, and sound absorption) are often included as part of a design intent statement. Should this occur, all other possible (and perhaps more desirable) solutions are ruled out by direct exclusion—if electric lighting is seen as an *intent*, then there is no place for daylighting. This does not serve a client or occupants well, and is also a disservice to the design team.

TABLE 1.1 Relationships between Design Intent, Design Criteria, and Design Tools/Methods

Issue	Design Intent	Possible Design Criterion	Potential Design Tools	Potential Implementation Method
Thermal comfort	Acceptable thermal comfort	Compliance with ASHRAE Standard 55	Standard 55 graphs/ tables or comfort software	Passive climate control and/or active climate control systems
Lighting level (illuminance)	Acceptable illuminance levels	Compliance with recommendations in the *IESNA Lighting Handbook*	Hand calculations or computer simulations	Daylighting and/or electric lighting
Energy efficiency	Minimal energy efficiency	Compliance with ASHRAE Standard 90.1	Handbooks, simulation software, manufacturer's data, experience	Envelope strategies and/or system and equipment strategies
Energy efficiency	Outstanding energy efficiency	Meet the requirements of the ASHRAE 50% *Advanced Energy Design Guide* for the building type	Handbooks, simulation software, manufacturer's data, experience	Envelope strategies and/or system and equipment strategies
Green design	Obtain green building certification	Meet the requirements for a LEED Gold rating	LEED materials, handbooks, experience	Any combination of approved strategies to obtain sufficient rating points

This book is a veritable catalog of design guidelines, methods, equipment, and systems that serve as means and methods to desired design ends. Sorting through this extensive information will be easier with specific design intent and criteria in mind. Owner expectations and designer experiences will typically inform design intent. Sections of the book that address fundamental principles will provide assistance with establishment of appropriate design criteria. Table 1.1 provides examples of the relationships between design intent, design criteria, and tools/methods.

1.5 VALIDATION AND EVALUATION

To function as a knowledge-based profession, design (architecture and engineering) must reflect upon previous efforts and learn from existing buildings. Except in surprisingly rare situations, most building designs are unique—comprising a collection of elements not previously assembled in precisely the same way. Most buildings are essentially a design team hypothesis—"We believe that this solution will work for the given situation." Unfortunately, the vast majority of buildings exist as untested hypotheses. Little in the way of performance evaluation or structured feedback from the owner and occupants is typically sought. This is not to suggest that designers do not learn from their projects, but rather that little research-quality, publicly shared information is captured for use on other projects. This is not an ideal model for professional practice from the perspective of society at large.

(a) Conventional Validation/ Evaluation Approaches

Design validation is very common, although perhaps more so when dealing with quantitative concerns than with qualitative issues. Many design validation approaches are employed, including hand calculations, computer simulations and modeling, physical models (of various scales and complexity), and opinion surveys. Numerous design validation methods are presented in this book. Simple design validation methods (such as broad approximations, lookup tables, or nomographs) requiring few decisions and little input data are typically used early in the design process. The later stages of design see the introduction of more complex methods (such as computer simulations or multistep hand calculations) requiring substantial and detailed input.

Building validation is much less common than design validation. Structured evaluations of occupied buildings are rarely carried out. Historically, the most commonly encountered means of validating building performance is the post-occupancy evaluation (POE). Published POEs have typically focused upon some specific (and often nontechnical) aspect of building performance, such as way-finding or productivity. The building commissioning process and evaluative case studies of projects are finding more application as approaches to building validation. Third-party validations, such as ENERGY STAR certified buildings and the Leadership in Energy and Environmental Design (LEED) rating system, are popular approaches.

(b) Commissioning

Building commissioning is a proven approach to quality assurance. An independent commissioning authority (an individual or, more commonly, a team) verifies that design decisions and related building assemblies, equipment, and systems can meet the owner's project requirements (design intent and criteria). Verification is accomplished through review of design documents, observation of component installation, and detailed testing of equipment and systems under conditions expected to be encountered with building use. Historically focused upon mechanical and electrical systems, commissioning is currently being applied to numerous building systems—including envelope, security, fire protection, and information systems. Active involvement of the design team is critical to the success of the commissioning process (ASHRAE, 2013; Grondzik, 2009).

(c) Case Studies

Case studies represent another approach to design/construction validation and evaluation. The underlying philosophy of a case study is to capture information from a particular situation and convey the information in a way that makes it useful to a broader range of situations. A building case study attempts to present the lessons learned from one case in a manner that can benefit other cases (future designs). In North America, the Vital Signs and Agents of Change projects have focused upon disseminating a building performance case study methodology for design professionals and students—with an intentional focus upon occupied buildings (à la POEs). The American Institute of Architects and the U.S. Green Building Council have developed case studies dealing with design process/practice. In the United Kingdom, numerous case studies have been conducted under the auspices of the PROBE (Post-Occupancy Review of Buildings and Their Engineering) project.

1.6 INFLUENCES ON THE DESIGN PROCESS

The design process may appear to revolve primarily around the needs of a client and the capabilities of the design team—as exemplified by the establishment of design intent and criteria. There are several other notable influences, however, that affect the conduct and outcome of the building design process. Some of these influences are historic and affect virtually every building project; others represent emerging trends and affect only selected projects. Several of these design-influencing factors are discussed below.

(a) Codes and Standards

The design of virtually every building in North America will be influenced by codes and standards. *Codes* are government-mandated and -enforced documents that stipulate minimum acceptable building practices. Designers usually interface with codes through an entity known as the *authority having jurisdiction*. There may be several such authorities for any given locale or project (fire protection requirements, for example, may be enforced separately from general building construction requirements or energy performance requirements). Codes essentially define the minimum response that society deems acceptable for dealing with a particular building design issue. In no way is code compliance—by itself—likely to be adequate to meet the needs of a client. On the other hand, code compliance is indisputably necessary.

Codes may be written in prescriptive language or in performance terms. A *prescriptive* approach mandates that something be done in a certain way. Examples of prescriptive code requirements include minimum R-values for roof insulation, minimum pipe sizes for a roof drainage system, or a minimum number of hurricane clips per length of roof. The majority of codes in the United States are fundamentally prescriptive in nature. A prescriptive code defines means and methods. By contrast, a performance code defines outcomes. A *performance* approach presents an objective that must be met. Examples of performance approaches to code requirements include a maximum permissible design heat flow through a building envelope, a minimum design rainfall that can be safely drained from a building roof, or a defined wind speed that will not damage a roof construction. Some primarily prescriptive codes offer performance "options" for compliance. This is especially true of energy codes and for smoke control requirements in fire protection codes.

Codes in the United States are continually in transition. Each jurisdiction (city, county, and/or state, depending upon legislation) is generally free to adopt whichever model code it deems most appropriate. Some jurisdictions (typically large cities) use homegrown codes instead of a model code. Historically, there were four model codes (the *Uniform Building Code*, the *Standard Building Code*, the *Basic Building Code*, and the *National Building Code*) that were used in various regions of the country. This regional code pattern has changed, with development and widespread use of a single model, the *International Building Code*, to provide a more uniform and standardized set of code requirements. Canada has its own *National Building Code*. Knowledge of current code requirements for a project is a critical element of the design process.

Standards are documents that present a set of minimum requirements for some aspect of building design. Such requirements have been developed by a recognized authority (such as Underwriters Laboratories, the National Fire Protection Association, or the American Society of Heating, Refrigerating and Air-Conditioning Engineers). Standards do not carry the weight of government enforcement that codes do, but they are often incorporated into codes via reference. Standards play an important role in building design and are often used by legal authorities to define the level of care expected of design professionals. Standards are typically developed under a consensus process with substantial opportunity for external review and input. *Guidelines* and *handbooks* are less formal than standards, usually with less formal review and/or consensus. *General practice*, the least formalized basis for design, captures the norm for a given locale or discipline. Table 1.2 provides examples of codes, standards, and related design guidance documents.

(b) Costs

Costs are a historic influence on the design process and are just as pervasive as codes. Typically, one of the earliest and strictest limits on design flexibility is the maximum construction budget imposed by the client. First cost (the cost for an owner to acquire the keys to a completed building) is the most commonly used cost factor. First cost is usually expressed as a maximum allowable construction cost or as a cost per unit area. Life-cycle cost (the cost for an owner to acquire and use a building for some defined period of time) is generally as important as, or more important than, first cost, but is often ignored by owners and usually not well understood by designers.

Over the life of a building, operating and maintenance costs can far exceed the cost to construct or acquire a building. Thus, whenever feasible, design decisions should be based upon life-cycle cost analyses and not simply first cost. The math of life-cycle costing is not difficult. The primary difficulties in implementing life-cycle cost analysis are estimating future expenses and the uncertainty naturally associated with projecting future conditions. These issues are not as difficult as they might seem, however, and a number of well-regarded life-cycle cost methodologies have been developed. Appendix J provides basic information on life-cycle cost factors and procedures. The design team may find life-cycle costing a persuasive ally in the quest to convince an owner to make important, but apparently expensive, decisions.

(c) Passive and Active Approaches

The distinction between passive and active systems may mean little to the average building owner, but it can be critical to the building designer and occupant. Development of passive systems must begin early in the design process, and requires early and continuous attention from the architectural designer. Passive system operation will often require the earnest cooperation and involvement of building occupants and users. Table 1.3 summarizes the identifying characteristics of passive and active systems approaches. These approaches are conceptually opposite in nature. Individual systems that embody both active and passive characteristics are often called hybrid systems. Hybrid systems are commonly employed as a means of tapping into the best aspects of both approaches.

The typical building will usually include both passive and active systems. Passive systems may be used for climate control, fire protection, lighting, acoustics, circulation, and/or sanitation. Active systems may also be used for the same purposes and for electrical distribution and signaling.

TABLE 1.2 Codes, Standards, and Other Design Guidance Documents

Document Type		Characteristics	Examples
Code		Government-mandated and government-enforced (typically via the building and occupancy permit process); may be a legislatively adopted standard	*Florida Building Code*; *California Title 24*; *Chicago Building Code*; *International Building Code* (when adopted by a jurisdiction)
Standard		Usually a consensus document developed by a professional organization under established procedures with opportunities for public review and input	ASHRAE Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*; ASTM E413-87, *Classification for Rating Sound Insulation*; ASME A17.1, *Safety Code for Elevators and Escalators*
Guideline		Usually a consensus document developed by a professional organization, but within a looser structure and with less stringent public review	ASHRAE Guideline 0, *The Commissioning Process*; *IESNA Advanced Lighting Guidelines*: NEMA LSD 12, *Best Practices for Metal Halide Lighting Systems*
Handbook		Development can vary widely—involving formal committees and peer review or single/multiple authors with no formal external review	*IESNA Lighting Handbook*; *ASHRAE Handbook—Fundamentals*; *NFPA Fire Protection Handbook*
Design guide		Development by experienced practitioners and educators; may offer schematic design process guidance, address architectural implications, links to other resources	Design procedures; general sizing procedures; green design strategies; case studies
General practice		The prevailing norm for design within a given community or discipline; least formal of all modes of guidance	System sizing approximations; generally accepted flashing details

Image Sources: code—used with permission of the International Code Council; standard—used with permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers; guideline and handbook—used with permission of the Illuminating Engineering Society of North America; general practice—used with permission of John Wiley & Sons.

Acronyms: ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers; ASME = American Society of Mechanical Engineers; ASTM = ASTM International (previously American Society for Testing and Materials); IESNA = Illuminating Engineering Society of North America; NEMA = National Electrical Manufacturers Association; NFPA = National Fire Protection Association.

(d) Energy Efficiency

Some level of energy efficiency is a societally mandated element of the design process in most developed countries. Code requirements for energy-efficient building solutions were generally instituted as a result of the energy crises of the 1970s and have been updated on a periodic basis since then. As with all code requirements, mandated energy efficiency levels represent the minimum performance level that is considered acceptable—not an optimal performance level. What is considered acceptable minimum performance has evolved over time in response to changes in energy costs and availability,

TABLE 1.3 Defining the Characteristics of Passive and Active Systems

Characteristic	Passive System	Active System
Energy source	Uses no purchased energy (no electricity, natural gas, fuel oil, etc.)—example: daylighting system	Uses primarily purchased (and nonrenewable) energy—example: electric lighting system
System components	Components play multiple roles in system and in the building as a whole—example: concrete floor slab that is structure, walking surface, and solar collector/storage	Components are commonly single-purpose elements—example: gas furnace
System integration	System is usually tightly integrated (often inseparably) with the overall building design—example: natural ventilation system using windows	System is usually not well integrated with the overall building design, often seeming an add-on—example: window air-conditioning unit
Passive and active systems represent opposing philosophical concepts. Design is seldom so straightforward as to permit the exclusive use of one philosophy. Thus, the hybrid system. Hybrid systems are a composite of active and passive approaches, typically leaning more toward the passive. For example, single-purpose, electricity-consuming (active) ceiling fans might be added to a natural ventilation (passive) cooling system to extend the performance of the system and thus reduce energy usage that would otherwise occur if a fully active air-conditioning system were turned on instead of the fans.		

and also in response to changes in the costs and availability of building technology.

In the United States, ANSI/ASHRAE/IESNA Standard 90.1 (published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, cosponsored by the Illuminating Engineering Society of North America, and approved by the American National Standards Institute) is the most commonly encountered energy efficiency benchmark for commercial/institutional buildings. Some states (such as California and Florida) utilize state-specific energy codes. Residential energy efficiency requirements are addressed by several model codes and standards (including the *International Energy Conservation Code*, the *International Green Construction Code*, and ANSI/ASHRAE Standard 90.2). Appendix H provides a sample of energy efficiency requirements from Standard 90.1.

Energy efficiency requirements for residential buildings tend to focus upon minimum envelope (walls, floors, roofs, doors, windows) and mechanical equipment (heating, cooling, domestic hot water) performance. Energy efficiency requirements for commercial/institutional buildings address virtually every building system (including lighting and electrical distribution). Most energy codes present a set of prescriptive minimum requirements for individual building elements, with an option for an alternative means of compliance to permit innovation and/or a systems-based design approach.

Efficiency is simply the ratio of system output to system input. The greater the output for any given input, the higher the efficiency. This concept plays a large role in energy efficiency standards through the specification of minimum efficiencies for many items of mechanical and electrical equipment for buildings. *Energy conservation* implies saving energy by using less. This is conceptually different from efficiency but is an integral part of everyday usage of the term. Energy efficiency codes and standards include elements of conservation embodied in equipment control requirements or insulation levels. Because of negative connotations that some associate with "conservation" (doing without), the term *energy efficiency* is generally used to describe both conservation and efficiency efforts in buildings.

The majority of energy efficiency standards deal solely with on-site energy usage. The reason for this approach lies in the controversy surrounding assigning site-source energy adjustment factors that do not disadvantage one fuel over another (there is no such controversy regarding renewable energy sources). Off-site energy consumption (for example, that required to transport fuel oil or natural gas, or the substantial process losses from electrical generation plants) is not typically addressed in energy efficiency regulations. A site-source focus can seriously skew thinking about energy efficiency design strategies, and this should be recognized by the design team. Off-site energy consumption that is directly tied to on-site consumption is real, can be substantial, and contributes to carbon emissions and fossil fuel depletion.

Passive design solutions usually employ renewable energy resources. Several active design solutions, however, also utilize renewable energy forms. Energy conservation and efficiency concerns are typically focused upon minimizing depletion of nonrenewable energy resources—even when not explicitly stated. The use of renewable energy sources (such as solar radiation and wind) changes the passive versus active discussion, should change the perspective of the design team, and may affect the way compliance with energy efficiency codes/standards is evaluated.

(e) Passive House Performance

At the risk of sowing confusion, it is appropriate to discuss *Passive House* performance in conjunction with energy efficiency. Passive House (with caps) is a building performance guideline with stringent energy benchmarks for both site (specifically space conditioning) and source energy. A Passive House (denoting annual energy performance) is not necessarily a house with passive heating/cooling/lighting systems—although a Passive House will have a well-designed enclosure system (which is very much a passive approach). To stir potential confusion a bit more, a Passive House does not need to be a house; it may be an office, school, or other building type. Some time on the horizon, the designation "Passive House" may change. In any event, a building certified under Passive House guidelines will be a highly energy-efficient building that approaches net-zero energy performance levels.

Currently, the benchmark requirements for Passive House performance in the United States (PHIUS) are:

Heating energy: $\leq$ 4.75 kBtu/ft^2/yr (15 kWh/m^2/yr)
Cooling energy: $\leq$ 4.75 kBtu/ft^2/yr (15 kWh/m^2/yr)
Total source (primary) energy: $\leq$ 38.1 kBtu/ft^2/yr (120 kWh/m^2/yr)

The general performance of a Passive House home ranks around 30–40 within the HERS rating spectrum (Fig. 1.10), depending on the size of the home, the climate, and if a solar thermal system is installed (without added photovoltaics). Several other performance targets (such as those set by LEED for Homes and Architecture 2030) are also shown in Fig. 1.10.

(f) Net-Zero Energy

Pushing energy efficiency toward its limits will lead to the realm of building performance associated with net-zero energy buildings. High efficiency alone is not sufficient to produce a net-zero building, but it is a practical prerequisite. By definition (National Renewable Energy Laboratory, NREL), a net-zero energy building will—on

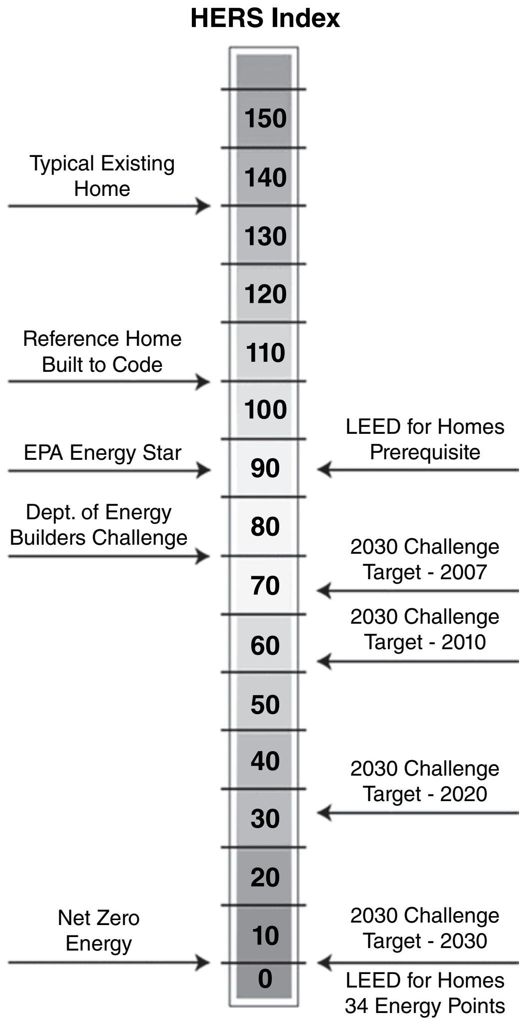


Fig. 1.10 *HERS (the Home Energy Rating System) is a relative comparison scale for residential energy performance. It sets baseline performance as 100 (which is linked to compliance with the 2006* International Energy Conservation Code*) and sets exemplary performance at 0, which is a net-zero energy residence. (Courtesy BuildingGreen, Inc.; used with permission.)*

an annual basis—produce as much energy from renewable resources (solar and wind, for example) as it consumes. Such a building will, despite aggressive energy-efficiency efforts, still use energy (for things such as domestic water heating, electric lighting, space heating/cooling, and appliances). Any such residual energy requirements will, however, be provided by renewable energy resources that match the magnitude of fossil-fuel-based energy consumption. Thus the use of the term “net-zero energy,” as opposed to “zero-energy” (which would essentially mean an unused building).

Looking at a net-zero energy building from another perspective—such a building may use energy derived from fossil fuels (such as electricity from a coal-fired power plant) to meets its programmatic and occupancy needs. But, every Btu (kWh) of energy from a nonrenewable resource must be matched by a Btu (kWh) of energy from a renewable resource. A net-zero energy building is not a no-energy building, and it is not a no-nonrenewable-energy building. It is, however, a low-energy building that employs at least 50% (annually) renewable energy. This is a big step on the road to sustainability. Sustainability (on the energy front) may lie in what some designers are describing as plus-energy buildings. More on sustainability in a following section.

There is no net-zero energy building code in the United States. Designers thus have some flexibility in defining a net-zero energy building within the clear limits of energy balance described above. This flexibility lies in the setting of system boundaries. The system boundaries may be spatial, temporal, and/or organizational. Life can become complicated. Some examples follow:

- Today, the most common perception of a net-zero energy building is one that is net-zero considering operational energy measured at the site boundary.
- The system boundaries may be expanded back to the proximate source of the building’s energy, such that source (versus site) energy is balanced; this is roughly three times more challenging for an all-electric building (as a result of generation and transmission losses that are not included in a site-based analysis).
- One could, in theory, extend the analysis boundary back to the ultimate source of the building’s energy (such as a coal mine or gas well); this is rarely done.
- Rather than considering only operational energy, the net-zero analysis boundary might be extended backward in time to include construction process energy (and perhaps design process energy).
- An owner might want to consider not just the building as the system, but also the organizational efforts supported by (or perhaps required by) the building; employee commuting energy might be considered, and/or the energy required to clean and maintain the building.

The source of renewable energy inputs to a net-zero building may also be addressed as a function of site boundary. For example, the renewable energy component might come from a green power purchase agreement (with the energy production occurring remotely), or the energy might be produced from systems located on or adjacent to a building. The authors’ philosophical preference is for site-based renewables—such that the design team is directly responsible for necessary energy production. In this case, the design process (relative to energy, and perhaps also water) will be seen as a job of balancing demand with supply.

(g) Green Building Design Strategies

Green design considerations—whether part of a formal building rating or just a matter of better design—are entering the design process for many buildings. Green design goes beyond energy-efficient design in order to address both the local and global impacts of building energy, water, and materials usage. Energy efficiency is a key, but not sole, element of green design. The concept that is broadly called “green design” arose from concerns about the wide-ranging environmental impacts of design decisions. Although there is no generally accepted concise definition of *green*, the term is typically understood to incorporate concern for the health and well-being of building occupants/users and respect for the larger global environment. A green building should maximize beneficial impacts on its direct beneficiaries while minimizing negative impacts on the site, local, regional, national, and global environments.

Several rating systems have found wide acceptance as benchmarks for “greenness.” These include the U.S. Green Building Council's LEED system, the Green Building Initiative's Green Globes Environmental Assessment system, and an international evaluation methodology entitled GBTool. Green building rating systems are in active use in the United Kingdom, Canada, and Japan. Most green building ratings systems are voluntary and would be correctly termed guidelines. A code-language set of green building design requirements, however, was developed by a coalition of professional organizations under the auspices of ASHRAE Standard 189, *Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings*.

Typical of green guidelines, the LEED systems (there are a number of rating schemes for a variety of project types) present a palette of design options from which the design team can select strategies appropriate for a particular building (Fig. 1.11) and its context. Amassing points for selected strategies provides a means of attaining green building status—at one of several levels of achievement—via a formal third-party certification procedure. Prerequisite design strategies (such as baseline energy efficiency and acceptable indoor air quality) provide an underpinning for the palette of optional strategies.

The emergence of green building rating systems has greatly rationalized design intent and design criteria in this particular realm of architecture. Prior to the advent of LEED (or GBTool), anyone could claim greenness for his/her designs. Although green design is entered into voluntarily (few codes currently require it, although a number of municipalities require new public buildings to be green), there are now several generally accepted standards against which performance can be measured. Appendix H provides an excerpt from the LEED-NC green building rating system to provide a sense of the scope of green building expectations.

(h) Carbon-Neutral Design

Climate change and global warming are growing concerns in the design community, as evidenced by the positive response of many professional organizations to the 2030 Challenge issued by Architecture 2030 (Architecture 2030). Design to reduce carbon emissions is becoming an issue on many building projects. The term *carbon-neutral design* is generally used to express this concern, and it accurately represents a primary design intent in a number of innovative projects. The Aldo Leopold Legacy Center in Baraboo, Wisconsin, is an exciting example of such a project.

Carbon dioxide (CO_2) is a major greenhouse gas; methane is another. Greenhouse gasses trap heat below the Earth's atmosphere in more or less the same way that glass traps heat from solar radiation in a greenhouse (or in a passive solar heating system). This trapping of heat increases temperatures and leads to climate change (ASES, 2007). Buildings are important contributors to carbon dioxide emissions and are therefore logical targets for mitigation in an attempt to reduce climate change potential. See Fig. 1.12 for an estimate of the role buildings play in producing CO_2 emissions.

(*a*)

(*b*)

Fig. 1.11 *(a) The Jean Vollum Natural Capital Center, Portland, Oregon. A warehouse from the industrial era was rehabilitated by Ecotrust to serve as a center for the conservation era. (b) LEED plaque on the front façade of the Vollum Center. The plaque announces the success of the design team (and owner) in achieving a key element of their design intent. (© 2004 Alison Kwok; all rights reserved.)*

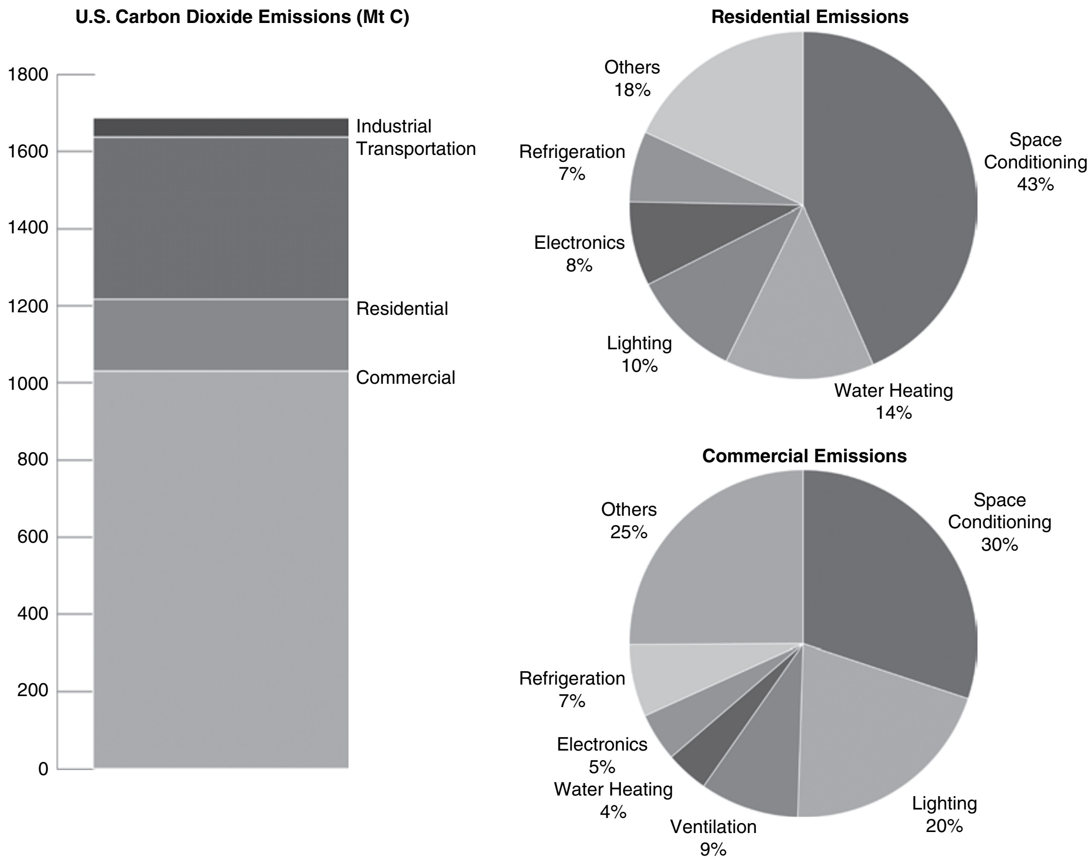


Fig. 1.12 *Contribution of the buildings sector (commercial and residential) to U.S. carbon dioxide emissions (Mt C = million metric tons of carbon dioxide), and the relative impact of various use categories on commercial and residential carbon impacts. (Drawing by Tyler Mavichien. Source:* 2011 Buildings Energy Data Book, *U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.)*

At an organizational scale, carbon (and other climate-changing) emissions may be classified in three broad categories (EPA), termed scopes:

- Scope 1: All direct GHG (greenhouse gas) emissions (such as from a gas-fired boiler or wood-burning stove)
- Scope 2: Indirect GHG emissions from consumption of purchased electricity, heat, or steam
- Scope 3: Other indirect emissions, such as from the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities (e.g., transmission and distribution) not covered in Scope 2, outsourced activities, waste disposal, etc.

These scopes apply at the scale of a single project, but as with net-zero energy analyses, it might be useful to consider that buildings produce (or are linked to) carbon dioxide emissions in several distinct ways that may be of concern to an owner:

- As a result of fossil fuel energy consumed during the design process (computer use, printing, site visits, etc.)
- As a result of fossil fuel energy consumed during the construction process (by equipment, worker commutes, site conditioning, etc.)
- Through the disposal of organic construction waste that decomposes
- As a result of ongoing fossil fuel energy consumption for heating, cooling, lighting, and building support operations
- As a result of vehicle use associated with building functions and siting (including fossil fuels used for employee commuting, product deliveries, etc.)
- As a result of waste produced by a building in operation

Of these various carbon release mechanisms, energy consumption for building operation is likely the largest contributor and the most readily available target for reductions. A reminder: Energy use itself is not the carbon culprit, but rather the use of fossil fuels to produce the energy.

Options for reducing carbon emissions from the operation of building systems include: improving the efficiency of building envelopes and systems (the ultimate, and unrealistic, goal being a zero-energy project); using renewable energy to meet the energy needs that remain after aggressive efficiency moves (the goal being a net-zero-energy building); and purchasing or obtaining carbon offsets (or credits) to mitigate the effects of residual carbon emissions not stemmed by efficiency and renewables. Carbon credits are somewhat controversial, being akin to buying one's way out of trouble—but they are an appropriate means of reducing carbon impacts beyond what can reasonably be achieved by skillful design solutions.

As cities begin requiring energy benchmarking for buildings, it is important for designers and building owners who need to quantify savings and create energy and carbon reduction goals to have an understanding of energy use and associated emissions metrics. Building plans, occupancy, energy loads, utility data, and areas associated with different uses are needed to calculate energy use intensity (EUI), which is measured in Btu/square foot/year. EUI is defined as the annual on-site intensity estimate for a design that accounts for all energy consumed at the building location (EPA Target Finder).

Another metric used to gauge how well a building performs in terms of greenhouse gas emissions is CO_2e. The term CO_2e is used because it takes into consideration several additional greenhouse gases such as methane and nitrous oxide (Bryan and Trusty, 2008). For example, on a personal scale, if we wanted to calculate the carbon emissions from plug loads in a typical U.S. single-family home, we would first calculate the EUI of all appliances (take kWh used in a year by all appliances, divide by the area of the house, convert kWh to Btu) and multiply by the operational CO_2e conversion for grid-delivered electricity. The EPA's ENERGY STAR program provides an online tool called Target Finder to allow designers who work with more complex projects to compare both the estimated building energy use and the estimated CO_2e emissions for their projects to a national standard.

At this time, there is no code, standard, or guideline that defines "carbon neutral" and only limited formal design guidance to assist in reaching that goal. This situation should change as interest in and demand for carbon-neutral projects grow.

(i) Design Strategies for Sustainability

Unlike green design, the meaning of "sustainability" in architecture has not yet been rationalized. The term *sustainable* is used freely—and often mistakenly—to describe a broad range of intents and performances. This is unfortunate, as it tends to make sustainability a meaningless term—and sustainability is far too important to be rendered meaningless by baseless claims. For the purposes of this book, sustainability will be defined as follows (paraphrasing the Brundtland Commission): *Sustainability involves meeting the needs of today's generation without detracting from the ability of future generations to meet their needs.*

Sustainability for most is essentially long-term survival under an assumed standard of living. In architectural terms, sustainability involves ensuring the survival of an existing quality of life for future generations. From the standpoint of energy, water, and materials, it can be argued that sustainability requires zero use of nonrenewable resources. Any long-term removal of nonrenewable resources from the environment will surely impair the ability of future generations to meet their needs (with fewer resources being available, as a result of our actions). Because sustainability is so important a concept and objective, the term should not be used lightly. It is highly unlikely that any single building built in today's economic environment can be sustainable (yielding no net resource depletion). Sustainability at the community scale is more probable; examples, however, are rare.

(j) Regenerative Design Strategies

Energy efficiency is an attempt to use less energy to accomplish a given design objective (such as thermal comfort or adequate lighting). Green design is an attempt to maximize the positive effects of design while minimizing the negative ones—with respect to energy, water, and material resources. Sustainable design is an attempt to solve today's problems while reserving adequate resources to permit future generations to solve their problems. Energy efficiency is a necessary constituent of green design. Green design is a necessary constituent of sustainable design. *Regenerative design* goes beyond sustainability.

The goal of energy efficiency is to reduce net negative energy impacts. The goal of green design is to reduce net negative environmental impacts. The goal of sustainability is to produce no net negative environmental impacts. The goal of regenerative design is to produce a net positive environmental impact—to leave the world better off with respect to energy, water, and materials. If design for sustainability is difficult, then regenerative design is even more difficult. Nevertheless, there are some interesting examples of regenerative design projects, including the Eden Project in the United Kingdom and the Center for Regenerative Studies (Fig. 1.13)

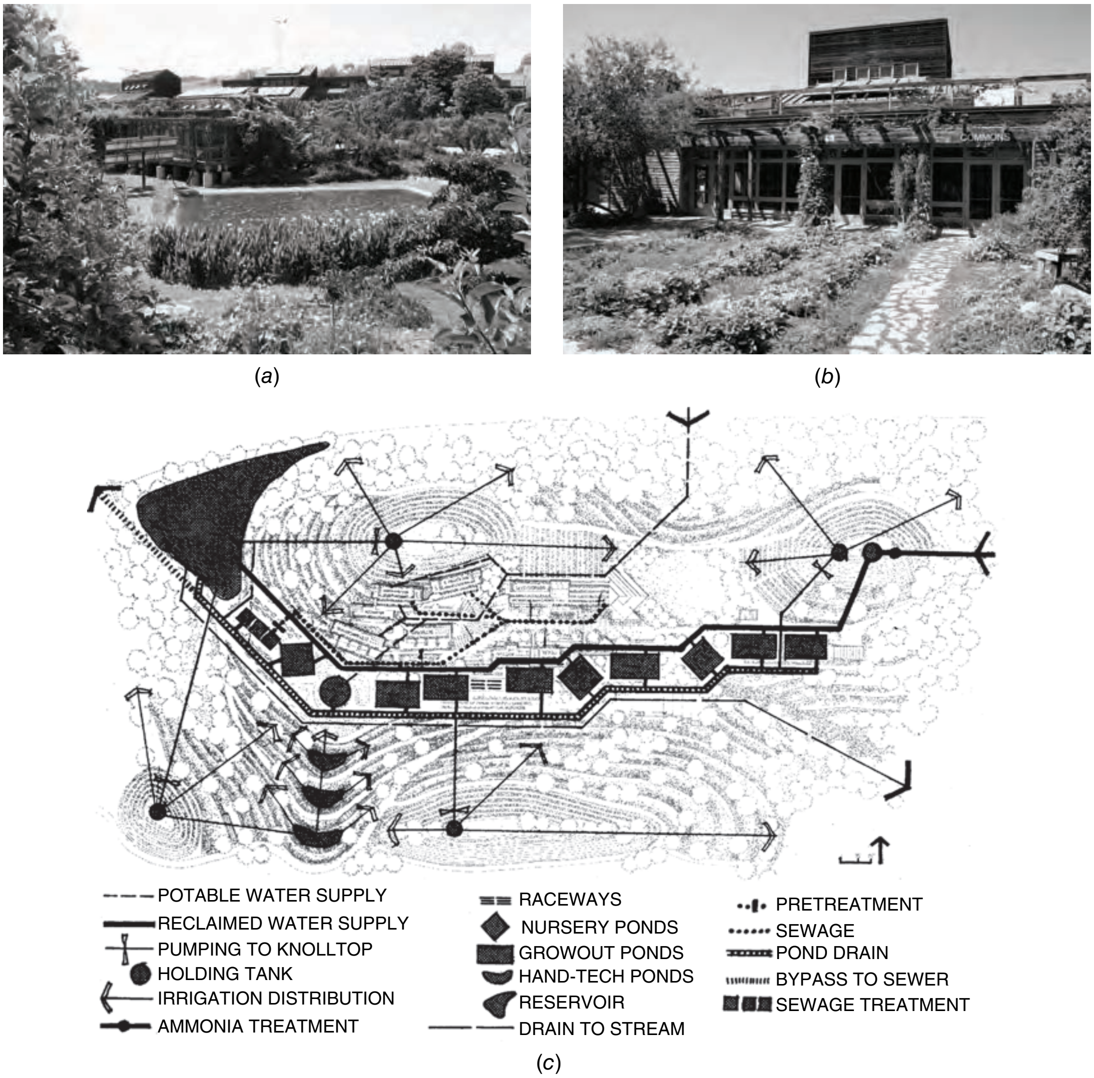


Fig. 1.13 *(a) The Center for Regenerative Studies (CRS), California Polytechnic State University–Pomona. (b) Plants provide water treatment and generate biomass in an aquacultural pond at the Center for Regenerative Studies, Cal Poly–Pomona. (c) Site plan for the CRS. It's not easy being regenerative—the highlighted elements relate only to the water reclamation aspects of the project. (Photos © 2013 Terri Meyer Boake; used with permission; drawing from John Tillman Lyle. 1994.* Regenerative Design for Sustainable Development. *John Wiley & Sons, Hoboken, New Jersey.)*

in the United States. Both projects involve substantial site remediation and innovative design solutions.

1.7 A PHILOSOPHY OF DESIGN

From a design process perspective, the operating philosophy of this book is that development of appropriate design intent and criteria is critical to the successful design of buildings and their mechanical and electrical systems. Passive systems should generally be used before active systems (this in no way denigrates active systems, which will be necessary features of almost any large-scale building); life-cycle costs should be considered instead of simply first cost; and green design is a desirable intent that will ensure energy efficiency and provide a pathway toward sustainability. Design validation, commissioning, and post-occupancy evaluation should be aggressively pursued.

John Lyle presented an interesting approach to design (that elaborates upon this general philosophy) in his book *Regenerative Design for Sustainable Development*. The following discussion presents an overview of his approach. The strategies provide design teams with varied opportunities to integrate site and building design with components and processes. Those strategies most applicable to the design of mechanical and electrical systems are presented here. This approach guided the design of the Center for Regenerative Studies at the California Polytechnic State University at Pomona, California (Fig. 1.13).

(a) Let Nature Do the Work

This principle expresses a preference for natural/passive processes over mechanical/active processes. Designers can usually find ways to use natural processes on site (Fig. 1.14), where they occur, in place of dependence upon services from remote/nonrenewable sources. Smaller buildings on larger sites are particularly good candidates for this strategy.

(b) Consider Nature As Both Model and Context

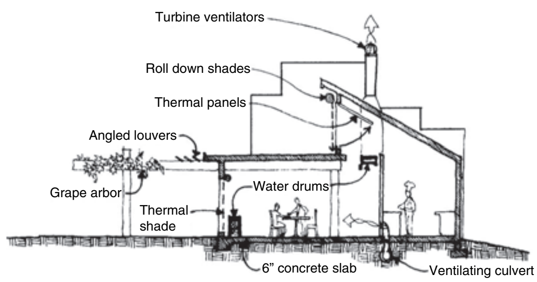
A look at this book reveals a strong reliance upon physical laws as a basis for design. Heat flow, water flow, electricity, light, and sound follow rules described by physics. This design principle, however, suggests looking at nature (Fig. 1.13) for biological, in addition to the classical physical, models for design. The use of a Living Machine to process building wastes, as opposed to a conventional sewage treatment plant, is an example of where this strategy might lead.

Fig. 1.14 *Letting nature do the work—via daylighting. Mt. Angel Abbey Library, St. Benedict (Mt. Angel), Oregon, designed by Alvar Aalto. (© Tyler Mavichien; used with permission.)*

(c) Aggregate Rather Than Isolate

This strategy recommends that designs focus upon systems, and not just upon the parts that make up a system—in essence, seeing the forest through the trees. The components of a system should be highly integrated to ensure workable linkages among the parts and the success of the whole. An example would be optimizing the solar heating performance of a direct-gain system involving glazing, floor slab, insulation, and shading components, even though such optimization might reduce the performance of one or more constituent parts of the system (Fig. 1.15).

(*a*)



(*b*)

Fig. 1.15 *Aggregating, not isolating. (a) The former Cottage Restaurant, Cottage Grove, Oregon, operated successfully with passive strategies for thirty years. (b) This section through the restaurant illustrates the substantial integration and coordination (aggregation) of elements typical of passive design solutions. (Photo by Lisa Leal; drawing by Michael Cockram; © 1998 by John S. Reynolds, A.I.A.; all rights reserved.)*

(d) Match Technology to the Need

This strategy seeks to avoid using high-grade resources for low-grade tasks (Fig. 1.16). For example, it is wasteful to flush toilets with purified water, but perhaps less obviously wasteful (but equally a mismatch) to use electricity (a very-high-grade energy form) to heat water for bathing. The concept of exergy (discussed in a subsequent chapter) relates to this design strategy.

A new tool offered by Architecture 2030 is the *2030 Palette*, an interactive online platform that gives the designer guiding principles, information, and resources to select appropriate technologies for a variety of scales: building, site, district, city, and region (http://2030palette.org/).

Fig. 1.16 *Match technology to the need. Sometimes it's the simple things that count. Keeping cool with a solar-powered fan cap.*

In 2007, the AIA published *50to50*, a resource offering 50 strategies with useful guidance to assist architects and the construction industry toward a 50% reduction in fossil fuels by 2010, and carbon neutrality by 2030. The strategies include a range of broad site and planning objectives to building-specific concepts. Each strategy includes an overview of the subject, typical applications, emerging trends, links to information sources, and important relationships to other carbon reduction strategies (American Institute of Architects, 2007).

(e) Seek Common Solutions to Disparate Problems

This approach requires breaking out of the box of categories and classifications. An understanding of systems should lead to an increased awareness of systems capabilities—which will often prove to be multidisciplinary and multifunctional. Making a design feature (Fig. 1.17) serve multiple tasks (perhaps mechanical, electrical, and architectural in nature) is one way to counteract the potential problem of a higher first cost for green design features. Solutions can be as simple and low-tech as using heat from garden composting to help warm a greenhouse.

(f) Shape the Form to Guide the Flow

The most obvious examples of this strategy are solar-heated buildings that are shaped (Fig. 1.18) to

Fig. 1.17 Seek common solutions. The "atrium" of the Hood River County Library, Hood River, Oregon, provides a central hub for the library, daylighting, views (spectacular), and stack ventilation. (© 2004 Alison Kwok; all rights reserved.)

gather winter sun, or naturally ventilated buildings shaped to collect and channel prevailing winds. Daylighting is another obvious place to apply the "form follows flow" strategy, which can have a dramatic impact upon building design efforts and outcomes.

(g) Shape the Form to Manifest the Process

This is more than a variation on the adage "If you've got it, flaunt it." This strategy asks that a building inform its users and visitors about how it works both inside and out (Fig. 1.19). In passive solar-heated and passively cooled buildings, much of the thermal performance is evident in the form of the exterior envelope and the interior space, rather than hidden in a closet or mechanical penthouse. Professor David Orr of Oberlin College addresses this issue succinctly by asking, "What can a building teach?"

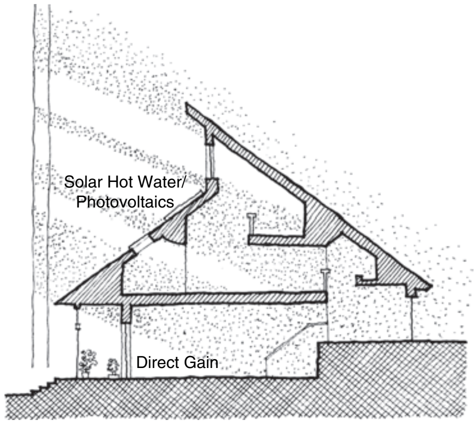


Fig. 1.18 Shaping the form to the flow. Using a "band of sun" analysis as a solar form giver (see Chapter 3 for further details). (Redrawn by Jonathan Meendering.)

(h) Use Information to Replace Power

This strategy addresses both the design process and building operations. Knowledge is suggested as a substitute for brute force (and associated energy waste). Designs informed by an understanding of resources, needs, and systems capabilities will tend to be more effective (successfully meeting intent) and efficient (meeting intent using fewer resources) than uninformed designs. Building operations informed by feedback and learning (Fig. 1.20) will tend to be more effective and efficient than static, unchangeable operating modes. Users of buildings can play a leading role in this approach by being allowed to make decisions about when to do what it takes to maintain desired conditions. Reliance on a building's users is not so much a direct energy saver—most controls use very little power—as it is an education. A user who understands how a building receives and conserves heat in cold weather is likely to respond by lowering the indoor temperature and reducing heat leaks. Furthermore, some studies of worker comfort indicate that with more personal control (such as operable windows), workers express feelings of comfort across a wider range of temperatures than with centrally controlled air conditioning.

(i) Provide Multiple Pathways

This strategy celebrates functional redundancy as a virtue—for example, providing multiple and

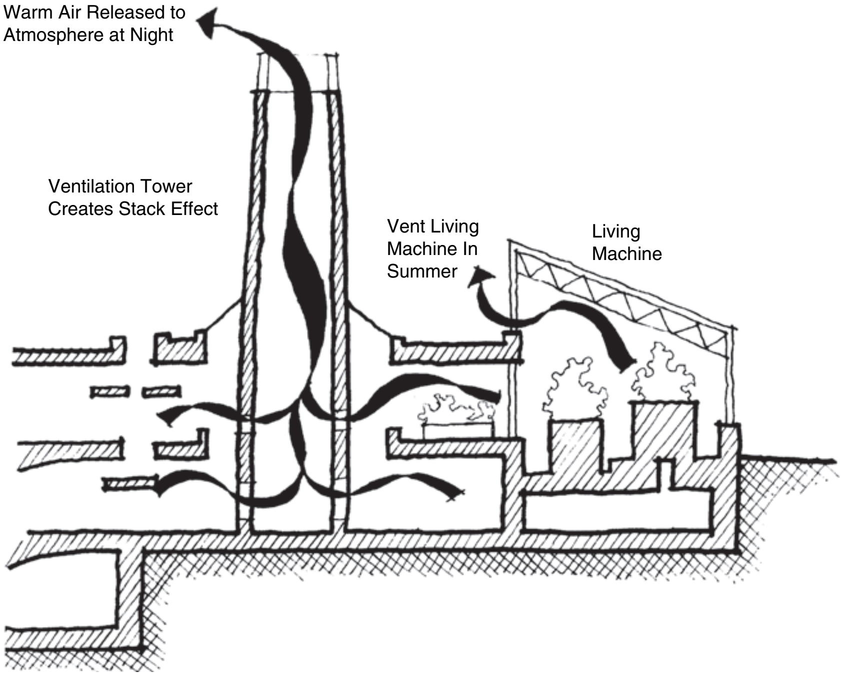


Fig. 1.19 *Shaping the form to the process. Stack effect ventilation is augmented by the building form in this proposal for the EPICenter project, Bozeman, Montana. (Courtesy of Place Architecture LLC, Bozeman, Montana, and Berkebile Nelson Immenschuh McDowell Architects, Kansas City, Missouri. Redrawn by Jonathan Meendering.)*

separate fire stairs for emergency egress. There are many other examples, from backup heating and cooling systems, to multiple water reservoirs and piping pathways for fire sprinklers, to emergency electrical and lighting systems. This strategy also applies to climate–site–building interactions in which one site-based resource may temporarily weaken but can be replaced by another (Fig. 1.21).

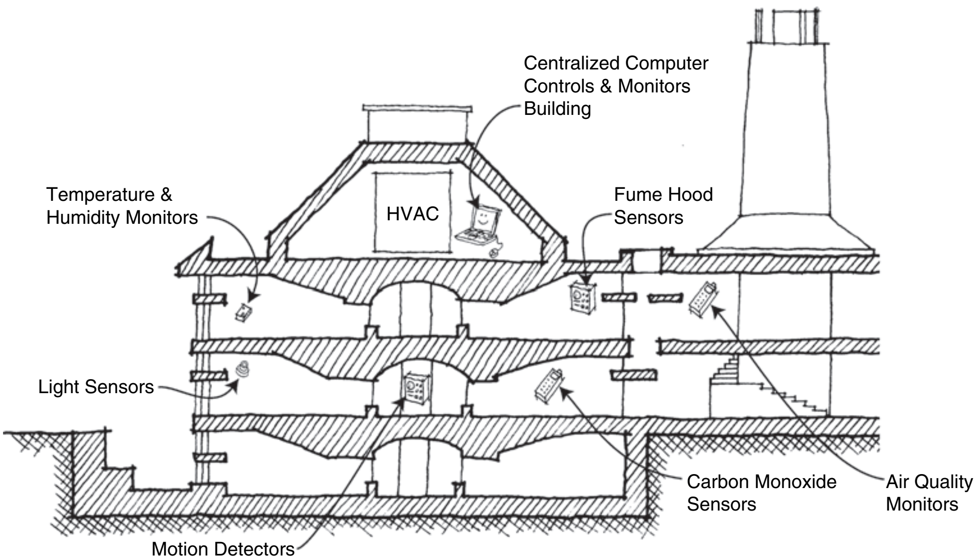


Fig. 1.20 *Use information to replace power. Section showing intelligent control system components for the proposed EPICenter project, Bozeman, Montana. (Courtesy of Place Architecture LLC, Bozeman, Montana, and Berkebile Nelson Immenschuh McDowell Architects, Kansas City, Missouri. Redrawn by Jonathan Meendering.)*

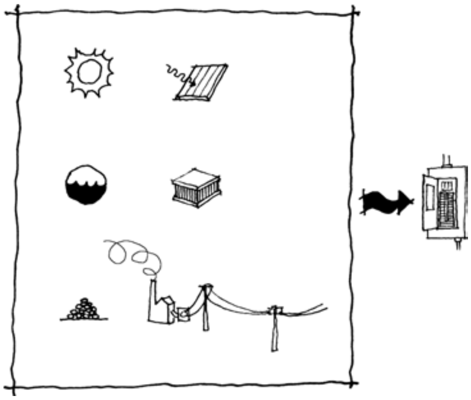


Fig. 1.21 *Providing multiple pathways. Three distinct sources of electricity are projected in this conceptual diagram for the proposed EPICenter project, Bozeman, Montana. (Courtesy of Place Architecture LLC, Bozeman, Montana, and Berkebile Nelson Immenschuh McDowell Architects, Kansas City, Missouri. Redrawn by Jonathan Meendering.)*

(j) Manage Storage

Storage is used to help balance needs and resources across time. Storage appears as an issue throughout this book. The greater the variations in the resource supply cycle, the more critical storage management becomes. Rainwater can be stored in cisterns, balancing normal daily demands for water against variable monthly supplies. The high variability of wind-generated electricity output can be managed with hydrogen storage, providing a combustible fuel that can be drawn on at a rate and time independent of wind speed.

On sunny winter days, excess solar energy reaching a room can be stored in thermally massive surfaces (Fig. 1.22), to be released at night. On cool summer nights, *coolth* (the conceptual opposite of heat) can be stored in these same surfaces and used to condition the room by day. Most storage solutions will strongly impact building architecture.

Fig. 1.22 *Manage storage. The 2007 MIT Solar Decathlon house features a Trombe wall made of translucent tiles to capture and store heat. (© Alison Kwok; all rights reserved.)*

1.8 LESSONS FROM THE FIELD

Bill Bordass, with the Usable Buildings Trust in the United Kingdom, has occasionally presented the Society of Building Science Educators (SBSE) listserv with summaries of lessons learned through extensive post-occupancy evaluation (POE) studies of buildings. This chapter is an appropriate place to digest some of the design recommendations that flow from these findings.

Bordass notes that building design features tend to have four attributes, sometimes possessing these attributes simultaneously:

- Physical: Fit and forget—if the designer and contractor have done a good job, the feature does its job and users can take it for granted.
- Administrative: Fit and manage—the feature needs looking after, and the question arises: Are the vigilance demands clear to the client and the operator? Often design features turn out to be more demanding on the operator than is realized at the time of design.
- Behavioral: Implement and internalize—the users have to understand the feature to make effective use of it. Often, however, the design intent is not clear, the feature has not been properly delivered, how it should be used has not been explained to the occupants, and use does not make sense or go with the flow of occupancy, even if explained.
- Perverse: Risk and freedom—often design features have both good and bad effects; it is easy for designers to get excited by the good ones and forget about the bad ones.

An intriguing recommendation, based upon the results of the Usable Buildings Trust POE studies is: "Keep it simple and do it well, and only after that begin to be clever." This guidance can be illustrated in the following sets of words to guide the wise designer:

- Process before product—then product and back to process
- Passive before active
- Simple before complicated

- Better before more
- 80 before 20 (use design time wisely)
- Robust before fragile
- Self-managing before managed
- Efficient before elaborate
- Trickle before boost
- Intelligible before intelligent
- Usable before alienating
- Forgiving before demanding
- Assets before nuisances
- Response before provision
- Off before on
- Cellular before open
- Experience before hope
- Thought before action
- Horses before carts

1.9 CASE STUDY—DESIGN PROCESS

Gilman Ordway Campus of the Woods Hole Research Center

PROJECT BASICS

- Location: Falmouth, Massachusetts, USA
- Latitude: 41.3°N; longitude: 70.4°W; elevation: near sea level
- Heating degree days: 5426 base 65°F (3014 base 18.3°C); cooling degree days: 2973 base 50°F (1652 base 10°C); annual precipitation: 45.5 in. (1156 mm) (degree day data are for New Bedford; rainfall is for Woods Hole)
- Building type: Remodeled and new construction; commercial offices and laboratory
- Building area: 19,200 ft^2 (1784 m^2); four occupied stories
- Completed February 2003
- Client: Woods Hole Research Center
- Design team: William McDonough + Partners (and consultants)

Background. The Gilman Ordway Campus of the Woods Hole Research Center involved both new construction and extensive remodeling of a venerable old house to provide office and laboratory facilities. The building generated a lot of interest, received a number of awards, and has collected detailed performance data. The clients are quite pleased with the facility and are using it as a vehicle to promote awareness of the environment and green design. (The discussion that follows was extracted from information provided by William McDonough + Partners and the Woods Hole Research Center.)

Context. The work of the Woods Hole Research Center is focused upon the related issues of climate change and defending the world's great forests. When a new headquarters was considered, it was decided that the facility should reflect the Research Center's core values, support its research and education mission, and provide a healthy environment for building occupants and the outside world. Fund-raising was a major issue for this project and substantially impacted the design process and scheduling. Perhaps the most valuable lesson to be learned from this project is the inestimable value of perseverance and the benefit that a clearly enunciated set of objectives (design intent and criteria) can provide in seeing a donor-supported project through to completion.

Design Intent. The Woods Hole Research Center project sought to demonstrate that a modern building can "harmonize with a habitable earth" while providing a healthy, comfortable, and enjoyable workplace. Enhanced productivity and job satisfaction for employees were key intents, as was far-beyond-code-minimum energy performance. In addition, the building was intended to serve as a teaching tool, providing an exemplar of a thoughtful approach to energy production and use, water quality and conservation, site design, and materials selection.

Design Criteria and Validation. The aggressive energy performance criteria set by the client and design team required the use of ENERGY 10 computer simulations and the ongoing services of an energy systems consultant. Interestingly, this same strong energy-related design intent allowed the retention of critical mechanical system elements during an extensive value engineering phase that cut approximately 15% from the construction budget. The owner retained an independent authority for building commissioning.

Key Design Features

- Extensive daylighting throughout the building
- Operable windows throughout the building
- An exceptionally tight and carefully detailed building envelope featuring triple-glazed windows and Icynene foam insulation (that also serves as an air barrier)
- A Ruck wastewater system, 95% on-site retention of storm water, and collection of rainwater for site irrigation
- A ground-source heat pump system for heating and cooling (coupled with a valence delivery system in office spaces)
- A rooftop, net-metered, photovoltaic array
- A 100-kW on-site wind turbine (added after initial construction)

Post-Occupancy Validation Methods. The client has installed an extensive energy-monitoring and -reporting system. Data collected by this system are available to the public via the World Wide Web (see "For Further Information," at the end of this section) and are also being used internally to optimize systems operations. Soils scientists from the Center are studying the effectiveness of the innovative septic system. In addition, the client has a very open and reflective attitude toward evaluation of the building and its systems. With a relatively small number of occupants, informal exchanges among Research

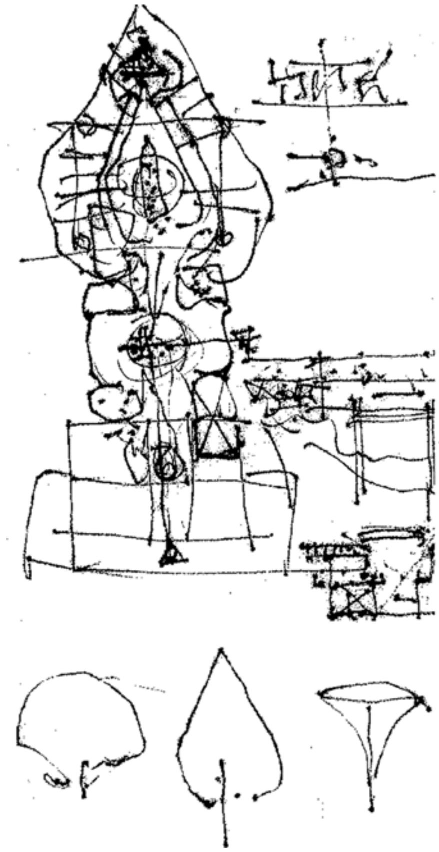


Fig. 1.23 *Initial concept sketch for the Woods Hole Research Center (WHRC)—the "leaf." This is an exceptional example of a conceptual design phase product. (© William McDonough + Partners; used with permission.)*

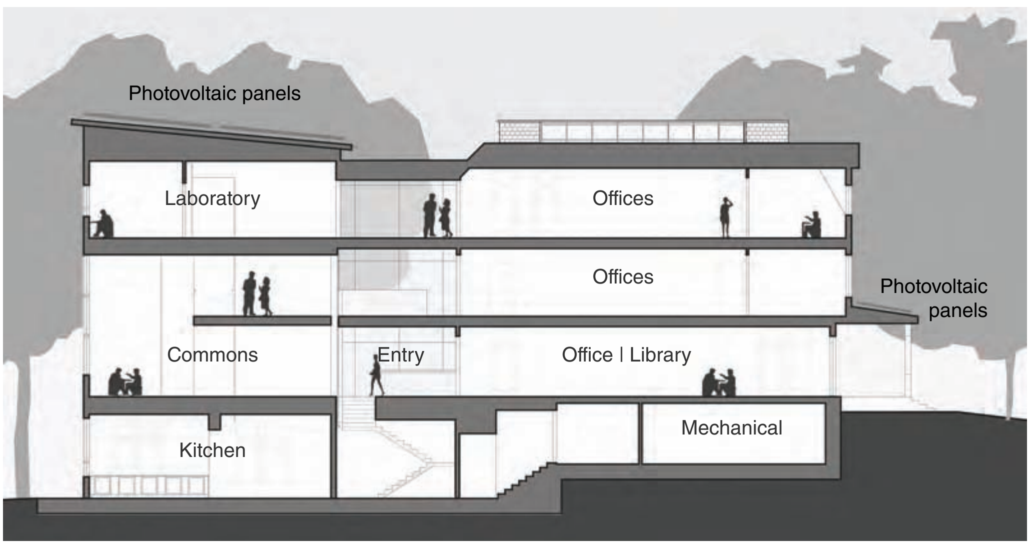


Fig. 1.24 *Schematic design phase section through WHRC showing spatial organization and photovoltaic array locations. (© William McDonough + Partners; used with permission.)*

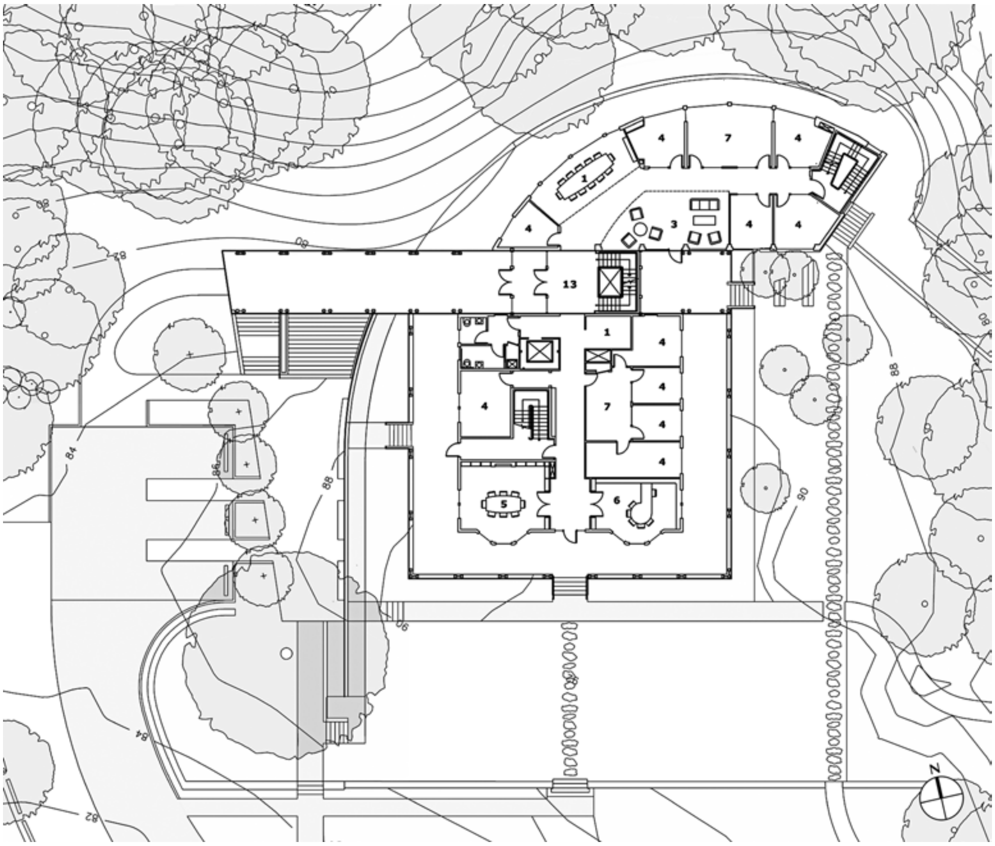


Fig. 1.25 The site/floor plan of WHRC is representative of the evolution of a project as it moves into and through the design development phase. (© William McDonough + Partners; used with permission.)

Center users appear to be proving an effective means of POE.

Performance Data. As this is a case study of design process as much as of a building, much of the following performance information relates to process outcomes. Energy data from three years of monitoring, however, are also given to describe success in the energy realm of design intent.

- The building design received an AIA/COTE Top Ten Green Projects Award (2004).

(*a*) (*b*)

Fig. 1.26 Construction phase photos of WHRC: (a) showing the structure for the new addition and the existing house being remodeled, (b) showing the merger of new and remodeled parts of the building as the envelope enclosure is finalized. (© William McDonough + Partners; used with permission.)

Fig. 1.27 Exterior photo of the completed and occupied WHRC. (© Alison Kwok; all rights reserved.)

- All of the interior finish woodwork is a Forest Stewardship Council (FSC) certified sustainably harvested product; exterior wood finishes are also FSC certified, including cedar shingles and siding and Brazilian *ipé* wood for the extensive porch, deck, and entrance stairway.
- Paints and coatings meet low volatile organic compound (VOC) criteria; no carpet is used in the building.
- A grant from the Massachusetts Renewable Energy Trust supported installation of a photovoltaic array consisting of 88 panels (each at 25 ft^2 [2.3 m^2]) that is expected to provide 37,000 kWh annually (compare this estimate with the measured data that follow).
- Measured data from the first year of occupancy show an energy consumption of about 20,000 Btu/ft^2 (63 kWh/m^2) per year; this is roughly 25% of the consumption of a typical office building and a 75% reduction from the energy density of the Research Center's previous facility.
- In 2010, the building consumed roughly 202,000 kWh of grid-provided electricity, the wind turbine produced 151,000 kWh of

Fig. 1.28 Bird's-eye view of the occupied WHRC building and site. Photovoltaic panels are a prominent feature on the roof. (© Cris Benton, kite aerial photographer and professor, University of California–Berkeley; used with permission.)

electricity, the PV system produced 33,000 kWh, and the net annual electricity consumption was 20,200 kWh.

- In 2011, the building consumed roughly 155,000 kWh of grid-provided electricity, the wind turbine produced 129,000 kWh of electricity, the PV system produced 30,000 kWh, and the net annual electricity consumption was -3800 kWh (thus operating as a net-plus building).
- In 2012, the building consumed roughly 146,000 kWh of grid-provided electricity, the wind turbine produced 109,000 kWh of electricity, the PV system produced 38,000 kWh, and the net annual electricity consumption was essentially zero.

FOR FURTHER INFORMATION

Summary information for the Woods Hole Research Center building can be accessed at: http://www.whrc.org/about/greencampus.html

Building performance information may be viewed from the project dashboard: http://buildingdashboard.net/whrc/woodwell/#/whrc/woodwell/

A description of the building and design process can be found at: http://www2.aiatopten.org/hpb/overview.cfm?ProjectID=257

References and Resources

Agents of Change. Department of Architecture, University of Oregon. http://aoc.uoregon.edu/

Aldo Leopold Legacy Center. www.aldoleopold.org/Visit/leopoldcenter.shtml

American Institute of Architects, AIA Sustainability Discussion Group. 2007. *50to50*, Washington, DC. http://www.aia.org/groups/aia/documents/pdf/aiab051123.pdf

ANSI/ASHRAE/IESNA. 2010. Standard 90.1: *Energy Standard for Buildings Except Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ANSI/ASHRAE. 2010. Standard 55: *Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Architecture 2030. http://www.architecture2030.org/

Architecture 2030 Palette. http://2030palette.org/

ASHRAE. 2013. *Guideline 0: The Commissioning Process*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Bryan, Harvey and Wayne Trusty. 2008. “Developing an Operational and Material CO2 Calculation Protocol for Buildings.” Presented at SB08 Conference, Melbourne, Australia.

Fuller, S. K. and S. R. Peterson. 1995. *Life-Cycle Costing Manual for the Federal Energy Management Program*. National Institute of Standards and Technology. Gaithersburg, MD. http://fire.nist.gov/bfrlpubs/

Green Building Initiative. Green Globes Environmental Assessment. Green Building Initiative. http://www.greenglobes.com/

Grondzik, W. 2009. *Principles of Building Commissioning*. John Wiley & Sons. Hoboken, NJ.

International Code Council. 2012. *International Building Code*. International Code Council. Falls Church, VA.

International Code Council. 2012. *International Energy Conservation Code*. International Code Council. Falls Church, VA.

C. Kutscher (ed.). 2007. *Tackling Climate Change in the U.S*. American Solar Energy Society. Boulder, CO.

Lyle, J. T. 1996. *Regenerative Design for Sustainable Development.* John Wiley & Sons. New York.

McLennan, J. R. 2004. *The Philosophy of Sustainable Design*. ECOTone Publishing Company, LLC. Kansas City, MO.

National Renewable Energy Laboratory NREL. http://www.nrel.gov/

National Research Council. 1995. *National Building Code of Canada.* National Research Council Canada, Institute for Research in Construction. Ottawa, ON.

PHIUS. Passive House Institute U.S. http://www.passivehouse.us/

Preiser, W. F .E. (ed.). 1989. *Building Evaluation.* Plenum Press. New York.

Solar Living Center (and The Real Goods Store). http://www.solarliving.org

Schaeffer, J. et al. 1997. *A Place in the Sun: The Evolution of the Real Goods Solar Living Center*. Chelsea Green Publishing Company. White River Junction, VT.

Usable Buildings. http://www.usablebuildings.co.uk/

U.S. Department of Energy. March 2012. *2011 Buildings Energy Data Book*. Office of Energy Efficiency and Renewable Energy. Washington, DC. (Regularly updated.)

U.S. Environmental Protection Agency (EPA). http://www.epa.gov/

U.S. Environmental Protection Agency (EPA) Target Finder. http://www.energystar.gov/buildings/service-providers/design/step-step-process/evaluate-target/epa%E2%80%99s-target-finder-calculator

U.S. Environmental Protection Agency (EPA). "EPA's Greenhouse Gas Emission Reductions." http://www.epa.gov/oaintrnt/ghg/

U.S. Green Building Council. LEED Rating System. http://www.usgbc.org/

Vital Signs. Center for Environmental Design Research, University of California–Berkeley. http://arch.ced.berkeley.edu/vitalsigns/

Wells, M. *Wilderness-Based Checklist for Design and Construction*. http://www.sbse.org/resources/docs/wells_checklist_explanation.pdf

World Commission on Environment and Development. 1987. *Our Common Future* (the Brundtland Report). Oxford University Press. Oxford, UK.

CHAPTER 2

Environmental Resources

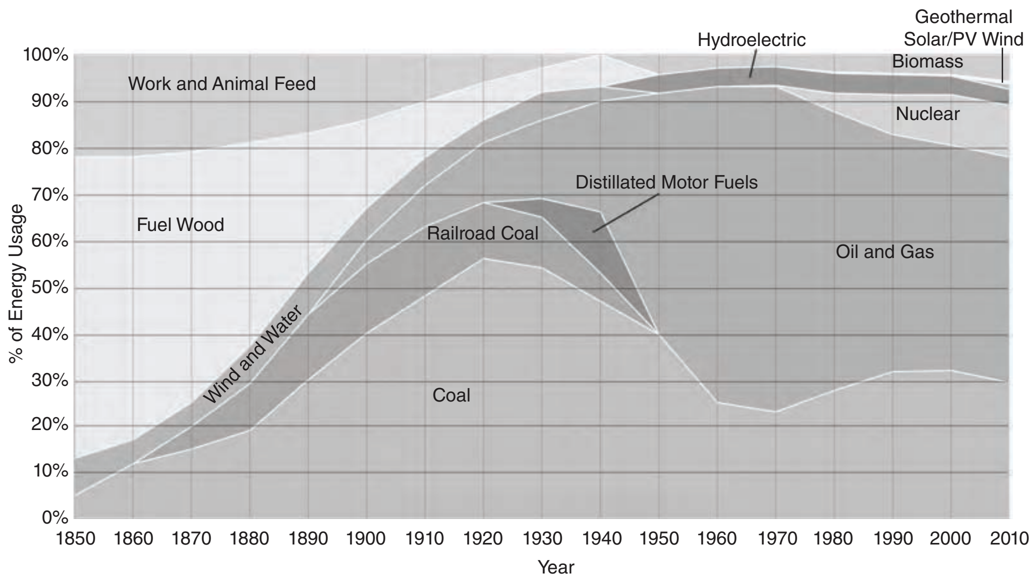
THE DESIGNER OF TODAY'S BUILDINGS WILL ADD OR reshape spaces on a planet that has, for eons, evolved by using renewable energy arriving from the sun at a generally fixed and limited rate. Suddenly (in geologic time) our planet is experiencing population growth, nonrenewable resource depletion, and measurable global climate change. Today's designers have available a declining, reservoir of materials, fossil fuel energy, and water resources. Do we continue to support a rapidly increasing population, where each person consumes more resources than did her/his grandparents? Eventually, our planet must live within a fixed budget of renewable energy, water, and materials. The question is: How can our present building design philosophies best move toward a necessary accommodation with sustainability? How can building designers be environmentally proactive instead of simply reactive?

Population growth is both the source of much of our work as buildings professionals and the underlying source of our greatest problems. Our planet did not support a human population of 1 billion until about 1830, at which time the United States depended almost entirely upon renewable energy provided by fuel wood and work animals; interior lighting was provided by candles or small oil or gas devices. In less than 200 years, 6 billion more people were added to our planet, and the United States shifted to almost total dependence upon nonrenewable fuels: coal, oil, and natural gas (Fig. 2.1). The building design process plays an active role in deciding where these people will live and work, and how much of what kinds of resources they will use. The mechanical and electrical systems that support our new buildings can be part of a growing problem or an important start to a necessary solution.

2.1 INTRODUCTION

Buildings depend upon energy and matter for their very existence and must pay heed to several fundamental rules of science. The first law of thermodynamics establishes the conservation of energy and matter (energy/matter can neither be created nor destroyed) and essentially states that you cannot get something for nothing. The second law of thermodynamics expresses the tendency toward disorder that is part of the normal nature of things. Entropy is a measure of such disorder; as disorder increases, so does entropy. The second law is a declaration against perpetual motion, and essentially states that not only can't you get something for nothing, you can't even break even, due to unavoidable losses (disorder) that contribute to increased entropy.

The construction and operation of buildings are ordering processes. Materials are mined or harvested, refined or shaped, placed in manufactured products, transported to a building site, and assembled. All of these processes consume energy and materials as the various building systems are established. The operation and maintenance of a building consume further resources, as conditions



Interactive Animation

Fig. 2.1 *U.S. fuel sources since 1850, showing a progression from dependence on renewable energy (wood and work animals) to fossil fuels (coal, then oil and gas). Wind and water power were shifted from mills to electricity generation between 1890 and the present. Although not shown here, much fossil fuel is now converted to electricity before use. (Data 1850–1950 are from Fisher, 1974; data 1951–2011 are from U.S. Energy Information Administration, 2012; Drawing by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

(temperatures, light levels, flows of water) are established that would not occur under less-ordered natural conditions. Maintaining building materials and systems over time against the forces of nature requires additional inputs of energy and materials. Buildings are inherently antientropic. This is not necessarily bad (learning and evolving are also antientropic), but it should be considered during the design process. As will be seen later in this chapter, buildings have a substantial collective impact on our patterns of energy, water, and materials consumption.

The design process should consider various scales of concern relative to the impacts of buildings upon the environment. One such scale is geographic. Geographic scales of concern include the microscale, the site scale, and the macroscale, with the building design focus historically being at the site scale. The terms *micro* (small) and *macro* (large) are not absolutely defined but are often referenced to a particular site. Thus, the area of influence of a microclimate is smaller than that of a macroclimate—but is usually also smaller than that of the site scale, often applying to one part of a site (perhaps with a steeper slope, lower elevation, or greater shading than other parts). The site scale is normally self-explanatory, running from property line to property line. Energy efficiency issues are typically and historically addressed at the site scale and often ignore (unfortunately) energy consumption off-site (such as electric power production losses or natural gas transportation losses). Renewable/passive energy systems must consider microscale effects (such as orientation) in order to be successful. Nonrenewable/active systems often are oblivious to any scale of concern.

Time is another, and very interesting, scale of concern to building design. The time frames typically addressed include *now* and *the future*—although *the past* is sometimes of concern with adaptive reuse and historic preservation projects. The concept of *the future* is usually left quite nebulous unless life-cycle costing is undertaken for a project, in which case the expected lifetimes of systems and equipment are explicitly estimated. It is clear that most buildings have a useful life of 25, 50, perhaps 100 years (or more). Stuart Brand provides an interesting look at buildings over time in *How Buildings Learn: What Happens after They're Built* (Brand, 1994). The problem with design for the future is that we don't know precisely what the future holds. Nevertheless, design for sustainability requires that the design team and the design process consider the needs of future generations. This makes sustainability a very challenging concept and highly subjective—but no less important than design for today.

2.2 ENERGY

Energy resources are broadly classified as renewable or nonrenewable. *Renewable* resources are those that are available on a recurring cycle without substantial depletion. They are, however, typically diffuse and can be consumed at a rate generally controlled by nature. For example, the influx of solar energy varies from day to day, but on average it should be available forever and at a reasonably predictable rate. Likewise, a woodlot produces a limited amount of wood per year but can do so for centuries if properly managed. An analogy for using renewable fuel sources is living on a fixed annual salary—with no hope for spectacular annual raises or unexpected bonuses, but with long-term stability if wisely managed.

Nonrenewable energy resources are those that, once exhausted, cannot be replaced in a time frame that is meaningful to the human race. Coal, oil, and natural gas are examples of nonrenewable energy resources. Using nonrenewable fuel sources is analogous to living off a one-time lottery win that can be spent in 1 year or over 50 years, depending upon needs and planning, but that is gone for good when it is all spent.

The United States, like other industrialized countries, has experienced an energy transition since the mid-1800s (Fig. 2.1) beginning with renewable energy sources, obtained locally, that provided relatively low-grade work: Animals pulled or pushed, and wood was burned to provide heated air, water, or steam. Buildings and people were directly affected by energy sources: Work animals needed to be fed, tended, and housed; fuel wood was cut nearby and stacked in large sheds (Fig. 2.2); fireplaces were social centers of buildings; and smoke from chimneys indicated activity inside. The side effects of energy use were also directly sensed—animal wastes, deforestation, and polluted air. Fuel use depended upon human labor. Architects of the era responded to the visual and spatial organization potentials of fireplaces and chimneys (Fig. 2.3).

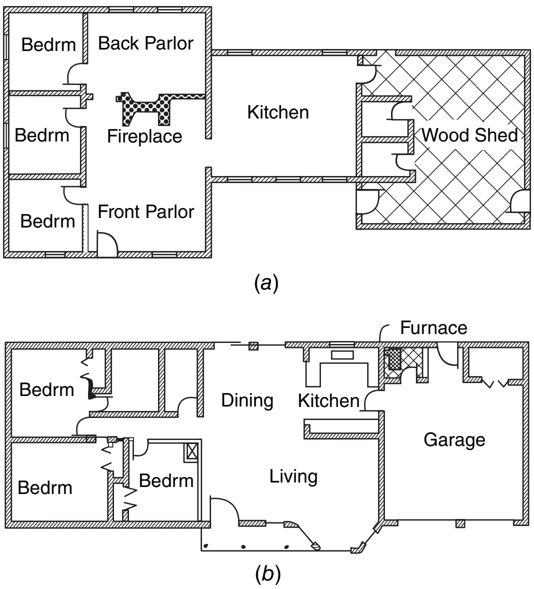


Fig. 2.2 Residential heating: past and present. (a) The house dependent on fireplaces or wood stoves also depends on someone to tend the fire. The warmer area near the fire in this early Oregon farmhouse was used for social purposes; the colder extremities served as sleeping areas and for storage of food and fuel. (Based upon a plan drawn by Philip Dole.) (b) The contemporary suburban home has either a small area for heating/cooling equipment or electric heat built into each room. Climate control equipment is no longer a major influence on building form.

Fig. 2.3 The fireplace and the more efficient wood stove can inspire architectural form. This chimney symbolizes permanence as well as protection against the cold. The major social space of the house is marked both by the arched window and by the fireplace chimney. (Photo by William Johnston.)

North America is now almost entirely dependent upon nonrenewable energy resources, an increasing proportion of which consists of imported oil and natural gas and electricity transported across substantial distances (Fig. 2.4). This situation is partly due to rapid growth in both population and per capita energy consumption. It is also due to the allure of highly concentrated energy available from fossil fuels, which encourages the use of high-quality energy sources such as electricity and natural gas for buildings and gasoline for transportation. People are now largely oblivious to their sources of energy: Electricity is generated in far-off power plants; natural gas arrives through buried pipelines, and fuel oil via supertankers. Buildings account for a good percentage of the world's total energy consumption. The impact of occupant experiences on energy use (and on building design and operation) tends to be diluted. Energy consumption is regulated by automatic controls, and heating and cooling equipment is hidden from sight. Building occupants/users—who often do not personally control a thermostat, see climate control equipment, or pay a utility bill—have no direct contact with or concern about energy resources. Clients hire architects to provide for function and comfort. Architects then pay engineers to design (and usually to successfully hide) mechanical and electrical equipment.

For several reasons, buildings designed today are likely to rely heavily upon electricity (Fig. 2.5), a situation that carries serious implications for resource depletion and environmental quality:

1. Consumption of electricity is expected to rise about twice as fast as overall energy demand, and we are often using electricity in place of other energy forms. Part of the reason for this is that, for some primary energy sources (such as coal, heavy fuel oil, or a nuclear reactor), generation of electricity for subsequent (secondary) distribution to buildings is the only convenient usage option.
2. Other than daylighting (unfortunately still rare in today's buildings), electricity is the only source for building illumination. Heat produced by electric lighting may reduce a building's need for space heating, but it increases its need for space cooling—and mechanical cooling is almost universally provided by electric air-conditioning equipment.
3. Plug loads in all types of buildings are increasing, while heating and cooling loads tend to be decreasing. Plug loads (appliances and equipment served by convenience receptacles) are totally electric.

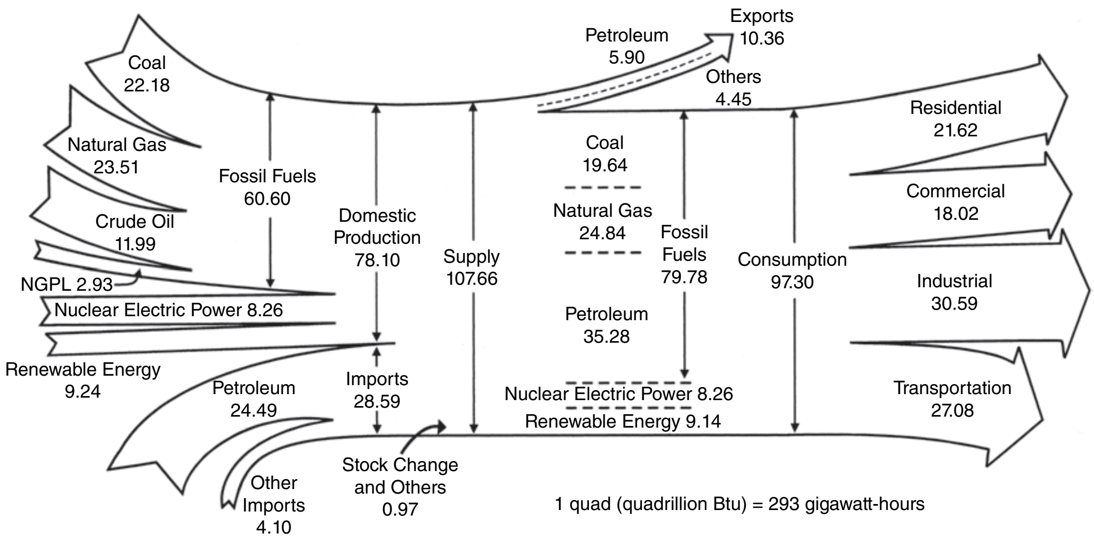


Fig. 2.4 *U.S. energy flow, 2011: sources and end uses. Fuel types and sources are shown to the left and end use sectors to the right. Note the importance of residential and commercial consumption to total U.S. consumption—and the currently minuscule contribution of renewable energy sources to the whole. (Redrawn by Ayush Vaidya using data from the U. S. Energy Information Administration, U.S. Department of Energy, Annual Energy Review, 2011. This data resource is updated on a regular basis, but the general patterns shown in this figure change slowly.)*

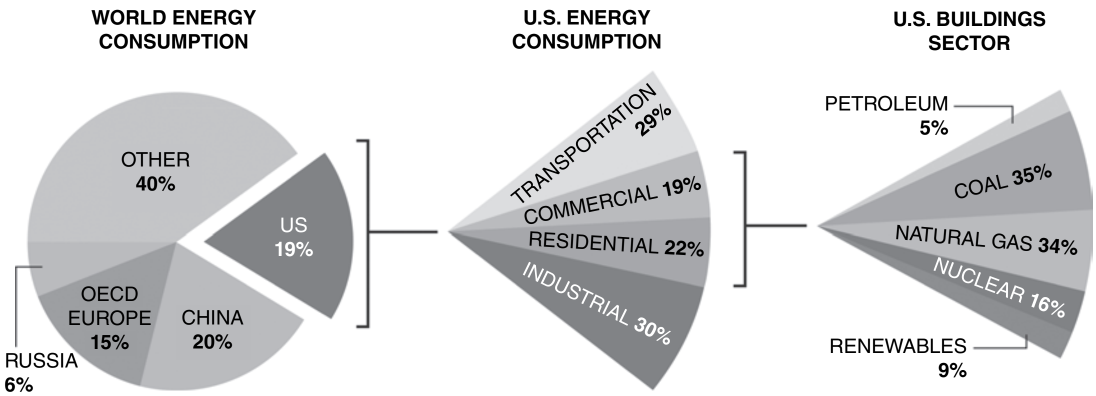


Fig. 2.5 *Energy resources as consumed by various end-use sectors in the United States, 2012. (Data and graphic from the USDOE's 2011 Buildings Energy Data Book.)*

4. Electricity is a convenient and versatile energy form; it not only serves such high-quality and highly concentrated (or *high-grade*) tasks as lighting and providing drive power via electric motors, it can also serve such low-quality, low-temperature (or *low-grade*) tasks as cooking, water heating, and space heating (Table 2.1). All-electric buildings are commonplace, even though they are subject to paralysis in blackouts—as any building dependent upon a single energy source is

TABLE 2.1 Energy End Use in U.S. Buildings, by Fuel Type (Quads)[a]

End Use	Natural Gas	Fuel Oil[b]	LPG	Other Fuel[c]	Renewable Energy[d]	On-Site Electric	On-Site		Primary Electric[e]	Primary	
							Total	%		Total	%
Space heating[f]	5.14	0.76	0.30	0.10	0.54	0.72	7.56	37.0	2.24	9.07	22.5
Space cooling	0.04					1.92	1.96	9.6	5.94	5.98	14.8
Ventilation[g]						0.54	0.54	2.6	1.66	1.66	4.1
Water heating	1.73	0.13	0.07		0.04	0.54	2.51	12.3	1.67	3.63	9.0
Lighting						1.88	1.88	9.2	5.82	5.82	14.4
Refrigeration[h]						0.84	0.84	4.1	2.62	2.62	6.5
Cooking	0.39		0.03			0.21	0.63	3.1	0.64	1.06	2.6
Wet clean[i]	0.06					0.33	0.38	1.9	1.01	1.06	2.6
Computers						0.38	0.38	1.9	1.19	1.19	2.9
Electronics						0.81	0.81	3.9	2.49	2.49	6.2
Other[j]	0.30	0.01	0.30	0.05	0.02	0.89	1.58	7.7	2.76	3.45	8.6
Adjustments[k]	0.68	0.25				0.44	1.37	6.7	1.35	2.28	5.7
Total	8.35	1.14	0.70	0.15	0.59	9.49	20.43	100	29.39	40.33	100

Source: U.S. DOE (2012). Data are for the year 2011.

[a]Quad = 10^{15} Btu (1 Ej).

[b]Includes distillate fuel oil (1.38 quads) and residual fuel oil (0.08 quad).

[c]Kerosene (0.08 quad) and coal (0.11 quad) are assumed to be attributed to space heating; motor gasoline (0.05 quad) is assumed to be attributed to "other" end uses.

[d]Passive solar space heating is not included. This column includes wood space heating (0.39 quad), geothermal space heating (<0.01 quad), solar water heating (0.05 quad), biomass (0.01 quad), and solar PV (<0.01 quad).

[e]Site-to-source electricity conversion = 3.22 due to generation and transmission losses.

[f]Includes electric furnace fans (0.25 quad).

[g]Commercial only (residential fan and pump energy use included proportionally in space heating and cooling).

[h]Includes refrigerators (1.37 quads) and freezers (0.43 quad) and commercial refrigeration.

[i]Includes clothes washers (0.10 quad), natural gas clothes dryers (0.07 quad), electric clothes dryers (0.76 quad), and dishwashers (0.08 quad).

[j]Includes commercial service station equipment, emergency electric generators, fuel oil cooking, natural-gas-driven pumps, natural gas lighting, automated teller machines, telecommunications equipment, medical equipment, residential pool/hot tub heating, residential small electric devices, outdoor grilles, outdoor natural gas lighting, and the like.

[k]Energy Information Administration (EIA) adjustment to address discrepancies among data sources. Energy is attributable to the residential and commercial buildings sector, but not directly to specific end uses.

vulnerable to disruptions. As shown in Table 2.1, of a total of 40 quads used for all building energy requirements, the primary energy used for electricity generation was 30 quads, accounting for roughly 75% of the total.

5. Electricity generated by thermal processes (except for cogeneration) delivers to the end user less than one-third of the total energy that goes into its production; more than two-thirds is usually lost as waste heat at the generating plant (Fig. 2.6). (In Table 2.1, for every 1 quad of electricity delivered, 3.22 quads were assumed used in generation.)

As we consume our planet's resources, including fossil fuels, designers might want to look to a return to reliance on renewable and sustainable energy. Such a future would be partially implemented by solar energy converted directly to electricity through photovoltaic (PV) modules placed on or near the building consuming the electricity. Solar collectors (some for heating water, others for producing electricity) and daylighting apertures would shape the roofs and facades of buildings. Building design professionals will decide whether to embrace or ignore such opportunities.

Hydrogen may be stored and distributed as a high-grade fuel, produced from water using electricity generated from renewable resources such as solar energy and wind. The lifetimes of mechanical and electrical equipment specified today will probably overlap such a future. In the future, lower-tech processes such as biomass conversion (combustion of wood and waste products) may develop faster than higher-tech processes such as PV. PV is growing very rapidly, though; its growth curve is as steep as that during the early years of computer technology. Some energy scenarios anticipate 50% of world energy demand being met by alternatives to fossil fuels by the year 2050. Other scenarios see no end to our consumption of fossil fuels and the related production of CO_2.

Today's fossil-fuel-based economy seems so entrenched as to defy a transition to renewable energy. Some doubt the capacity of renewables and ask: Is solar energy adequate for our energy needs? Table 2.2 compares the amount of solar energy received at the Earth's surface in a single day with other energy phenomena. There appears to be more than adequate global resource availability—given

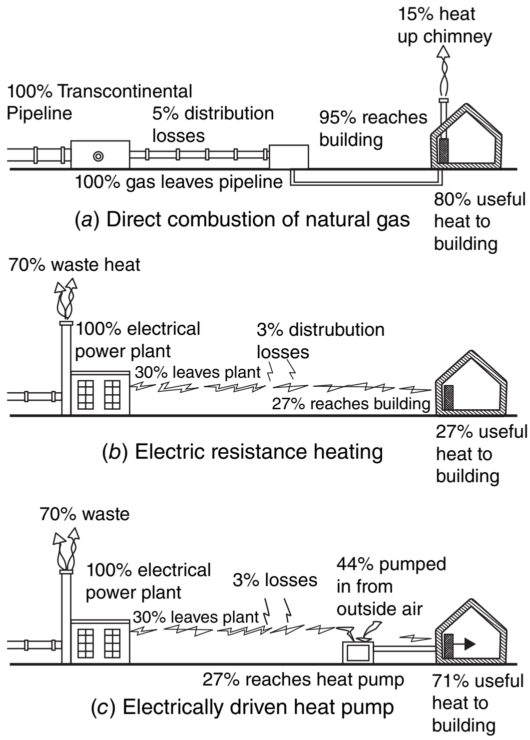


Fig. 2.6 *Variations on higher-grade energy and lower-grade tasks. (a) Natural gas (a fossil fuel) is often burned in furnaces to provide low-grade space heating. With today's high-efficiency furnaces, well over 90% of the energy in the gas is delivered to the building as space heat. (b) However, when that natural gas is used instead to generate electricity, and electric resistance is used for space heating, the inefficiencies at the electric power plant cut deeply into the available useful energy: Only about 27% is delivered to the space as heat. (c) On the other hand, when the electricity generated by natural gas is used to drive a heat pump, and the outdoor air is above freezing, about 71% of the energy in the gas is delivered as space heat. (Drawing by Michael Cockram; © 1998 by John S. Reynolds, A.I.A.; all rights reserved.)*

a will to move toward renewable and site-based resources. Energy efficiency and conservation efforts will play a critical role in making such a transition feasible.

To date, societal focus has been primarily upon using less energy—involving energy efficiency (using energy more effectively) and energy conservation (simply using less energy). The oil embargo of the 1970s spurred the development of building energy-efficiency standards, which have remained a fixture of building design ever since. In general, such standards seek to reduce building energy consumption—not to shift energy resources from nonrenewables to renewables. The green building design movement

TABLE 2.2 Daily Arrival of Solar Energy on Earth Compared to Other Energy Quantities

Solar energy received each day	1
Melting of an average winter's snow during the spring	$^1/_{10}$
A monsoon's circulation between ocean and continent	$^1/_{100}$
Use of energy by all mankind in a year	$^1/_{100}$
A mid-latitude cyclone	$^1/_{1000}$
A tropical cyclone	$^1/_{10,000}$
Kinetic energy of motion in Earth's general circulation	$^1/_{100,000}$
The first hydrogen bomb	$^1/_{100,000}$
A squall line containing severe thunderstorms	$^1/_{1,000,000}$
A thunderstorm	$^1/_{100,000,000}$
The first atomic bomb	$^1/_{100,000,000}$
The daily output of Boulder Dam	$^1/_{100,000,000}$
A typical local rain shower	$^1/_{10,000,000,000}$
A tornado	$^1/_{100,000,000,000}$
Lighting New York City for one night	$^1/_{100,000,000,000}$

Source: Reprinted by permission from Lowry, W. 1988. *Atmospheric Ecology for Designers and Planners*. Peavine Publications, McMinnville, OR.

has provided momentum for a serious look at both reduced energy use and the use of energy from renewable resources (see Appendix H).

2.3 WATER

The efforts of architectural and engineering professionals toward more resource-efficient buildings have, for the past several decades, focused primarily upon energy. This focus has been warranted by the economic, environmental, and societal effects of consuming nonrenewable energy resources, amplified by the physical limits imposed by entropy. There is no option for the reuse or recycling of fossil fuels (as may be done with water and materials) and little opportunity for downstream use of the energy produced by such fuels.

Water, however, must be reused. A quote generally attributed to *National Geographic* (October 1993) made this point succinctly: "All the water that will ever be is, right now." Although water is a recyclable resource, it is not a renewable resource (no new daily supplies are being delivered to Earth). Water concerns have reached crisis level in many parts of the world, and water may well be the emerging limit to growth and development—especially locally and regionally—rather than energy. Periodic water rationing is an unpleasant fact in many areas.

Where water is found is not necessarily where it is needed. Concerns about a viable supply of potable water have dominated politics and civil engineering in the arid western United States for a century. Surprisingly, Tampa, Florida, in the heavily rained-upon Southeast, has a desalination plant to provide water for a bizarrely under-resourced region. Table 2.3 compares regional water resources with sustainable water usage capacity; it is clear that some areas of the United States now have serious water shortages. Accelerated depletion of underground water stocks (from aquifers, which are analogous to fossil fuel reserves) and maxed-out imports (both hydrologically and politically) suggest more trouble on the way. On a global scale, the disparities become even greater. Mostafa Tolba, former executive director of the UN Environment Program, speaking of the international picture, notes: "We used to think that energy and water would be the critical issues for the next century. Now we think water will be the critical issue" (UNH, 2004).

As with energy, per capita use of water involves more than consumption within a building. In the case of energy, transportation and industrial uses influence per capita consumption; with water, energy production and agricultural uses play a role. About half of all U.S. fresh and saline water withdrawals in 2005 were used in conjunction with thermoelectric power generation. Most of this was surface water used for once-through cooling at power plants. Withdrawals for this use have been relatively stable since 1985. (In a quirky energy-water connection, the California State Water Resources Control Board estimates that 6.5% of California's total electricity use is related to pumping and treating water.)

Irrigation remains the largest use of freshwater in the U.S. In 1950, irrigation accounted for about

TABLE 2.3 Comparison of Regional Water Use versus Resources for the Continental United States

Water Resources Region[a]	Consumptive Use	Renewable Water Supply[b]	Ratio (Use/Supply)
New England	0.6	78.4	0.8%
Mid-Atlantic	1.3	80.7	1.5%
South Atlantic/Gulf	6.1	233.5	2.6%
Great Lakes	1.9	74.3	2.6%
Ohio	2.3	139.6	1.7%
Tennessee	0.3	41.2	0.7%
Souris-Red-Rainy	0.5	6.5	7.7%
Upper Mississippi	2.3	77.2	3.0%
Lower Mississippi	40.3[c]	484.8	8.3%
Missouri	17.5	52.9	33.1%
Arkansas-White-Red	9.6	68.7	14.0%
Texas Gulf	9.1	33.1	27.5%
Rio Grande	3.5	5.4	64.8%
Upper Colorado	4.2	13.9	30.2%
Lower Colorado	10.6[c]	10.3	103.0%
Great Basin	3.5	10.0	35.0%
Pacific Northwest	11.2	276.2	4.1%
California	25.8	74.6	34.6%

Source: Adapted from *United States Geological Survey*, 1984, with 1995 updates for water usage: http://water.usgs.gov/watuse/misc/consuse-renewable.html

Although based upon 1995 data, this is the most recent public document dealing with this issue.

[a]These are water resource areas generally independent of state boundaries.

[b]Renewable water supply represents a long-term sustainable resource: precipitation plus imports less evaporation, exports, and water needed to maintain minimal stream flows.

[c]These values are for the entire river system.

65% of total water withdrawals, excluding those for power generation. Historically, more surface water than groundwater has been used for irrigation. The percentage of total irrigation withdrawals from groundwater has fluctuated, from 23% in 1950 to 42% in 2000 to 37% in 2005. Irrigated acreage more than doubled between 1950 (25 million acres) and 1980 (58 million), then increased only slightly to 60 million acres in 2005 (USGS, 2009).

Public water supply withdrawals in 1950 were 14 Bgal/day (53 GL/day); in 2000, this use had reached approximately 45 Bgal/day (163 GL/day). In 2000, about 86% of the U.S. population obtained drinking water from public suppliers, compared to 62% in 1950. Surface water provided the majority of this resource. Potable water obtained from a surface source via a public supply system is the norm (increasing from 62% of the U.S. population in 1950 to 86% in 2005); private well systems are less common than in the past. As with energy, population increases are increasing overall water consumption, while conservation efforts provide some counterbalancing effect.

Water-efficiency and conservation standards are not nearly as extensive or ubiquitous as energy-efficiency standards, although most building users are aware of low-flow toilet requirements, flow restrictors for showers, and self-closing bathroom faucets in public facilities. Surprisingly, given the few design restrictions that exist, per capita water use in the United States has remained flat for the past several years—and is currently 25% lower than in the late 1970s. This is partly because overall per capita use involves important sectors other than buildings (agriculture and power generation, for example) and partly due to increasing awareness of the value of water.

As with renewable energy sources, green building design efforts have also increased awareness of and design for water supply savings and alternatives. Part V, "Water and Waste," covers a number of design approaches for water and waste that would likely be used in a green building. The role of water in the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) rating system is outlined in Appendix H.

2.4 MATERIALS

A global or even countrywide perspective on materials resources is more difficult to obtain than is the case for energy and water. In the United States there appears to be a general upward trend in per capita consumption of materials. In the early 1900s, per capita consumption was around 3 metric tons per person, about 50% of which was construction materials; in 1950 it was about 6 tons, with about 60% in construction materials; and in 1995 about 10 tons, with about 65% in construction materials.

Given the scarcity of quantitative data, a qualitative comparison with water must suffice. Many materials used for building construction and repairs come from a generally fixed resource base. Like water, materials (at least many) may be recycled, but there is a fixed quantity of resources available on Earth. For many materials, what we have now is what we will have in the future, a major exception being those organic materials (such as fiber products) that are renewable.

Finding adequate materials resources for a building directly from the building site is rare: wood, straw, and earthen construction systems, for example, require large land areas to supply the materials for even a small building. The most commonly used construction systems involve materials brought to a site from some distance. A designer can generally select between imported renewable or nonrenewable materials and between imported virgin or recycled materials. The common thread is *imported*—not necessarily from overseas, but from a distance. Reducing the transportation distance and finding local materials when available are emerging design strategies.

Wood is the only renewable construction material currently in wide use in North America. It is easily worked, supports a wide variety of finishes, has moderate structural strength, requires regular maintenance for long life, catches fire easily, and has only moderate value either as thermal mass or as insulation. This common building material illustrates the impact a rapidly increasing population can have on a fixed, even if renewable, resource base. As huge old trees are harvested to the point of disappearance, growing demand for wood outstrips the supply available from younger, smaller trees. New production methods are devised (such as laminates, particle board, and engineered lumber) to allow large wood members to be constructed from smaller timber. The value of salvaged older wood members increases.

Nonrenewable materials are by far the most commonly used constituents of mechanical and electrical systems; metals and plastics predominate. Their advantages include strength, durability, fire resistance, and conductivity or resistivity as required. Most such materials are obtained, however, at a significant energy cost to mine, manufacture, transport, and install them for our use.

With rapidly increasing demand for both renewable and nonrenewable materials, how should a designer on a planet with fixed resources respond? What are the key materials issues that the design team ought to consider?

(a) Embodied Energy

One issue is *embodied energy*, a complex and therefore elusive indicator of how much energy must be invested to mine/harvest/produce, fabricate, and transport a unit of building material. Table 2.4 summarizes information on embodied energy for common units of today's prevalent construction materials. The units shown in the table refer to equivalent carbon dioxide (CO_2e), defined as the concentration of CO_2 that would cause the same damage as certain concentrations of greenhouse gases (e.g. methane, perfluorocarbons). The apparently simple values for any given material are complicated by variations in raw resource availability (more difficulty in extracting materials requires more energy), variations in distance from raw resource to manufacturing locations, and variations in the fuels used (and their efficiency of use) in the refining or fabricating processes.

Consider two alternatives for exterior wall cladding: wood siding and aluminum siding. Wood contains embodied energy from a renewable resource—the sun. It takes the energy of human beings and chain saws to cut the trees and fuel to haul them, perhaps 100 miles (160 km), to a mill. At the mill, more energy is invested as logs become lumber, and still more energy is used as lumber becomes finished siding—which is then transported to a construction site. Aluminum begins as bauxite, which requires energy to mine, then more energy to ship great distances to smelters, which use large

TABLE 2.4 Approximate Total Embodied Energy and Carbon in Building Materials[a]

	Embodied Energy & Carbon Coefficients			Comments
Materials	**EE - MJ/kg**	**EC - $kgCO_2/kg$**	**EC - $kgCO_2e/kg$**	**EE = Embodied Energy EC = Embodied Carbon**
		Asphalt		
Asphalt, 4% (bitumen) binder content (by mass)	2.86	0.059	0.066	1.68 MJ/kg Feedstock Energy. Modeled from the bitumen binder content. The fuel consumption of asphalt mixing operations was taken from the Mineral Products Association (MPA). It represents typical UK industrial data. Feedstock energy is from the bitumen content.
Bitumen	51	0.38–0.43	0.43–0.55	42 MJ/kg Feedstock Energy. Feedstock assumed to be typical energy content of Bitumen. CO_2 emissions are particularly difficult to estimate, range given.
		Bricks		
General (Common Brick)	3.00 (6.9 MJ per brick)	0.23 (0.53 $kgCO_2$ per brick)	0.24 (0.55 $kgCO_2$ per brick)	Assuming 2.3 kg per brick
Limestone	0.85			
		Carpet		
General Carpet	74 (187 per sqm)	3.9 (9.8 per sqm)		
Wool	106.00	5.53		
		Cement		
General (UK weighted average)	4.5	0.73	0.74	Weighted average of all cement consumed within the UK. This includes all factory made cements (CEM I, CEM II, CEM III, CEM IV) and further blending of fly ash and ground granulated blast furnace slag. This data has been estimated from the British Cement Association's factsheets. 23% cementitious additions on average.
		Clay		
General (Simple Baked Products)	3.00	0.23	0.24	General simple baked clay products (inc. terracotta and bricks)
Tile	6.50	0.45	0.48	
Vitrified clay pipe DN 100 & DN 150	6.20	0.44	0.46	
		Concrete		
General	0.75	0.100	0.107	It is strongly recommended to avoid selecting a "general" value for concrete. Selecting data for a specific concrete type (often a ready mix concrete) will give greater accuracy, please see material profile. Assumed cement content 12% by mass.
		CONCRETE BLOCKS (ICE CMC Model Values)		
Block - 8 MPa Compressive Strength	0.59	0.059	0.063	Estimated from the concrete block mix proportions, plus an allowance for concrete block curing, plant operations and transport of materials to factory gate.
Block - 10 MPa	0.67	0.073	0.078	
Block - 12 MPa	0.72	0.082	0.088	
Block - 13 MPa	0.83	0.100	0.107	
Autoclaved Aerated Blocks (AAC's)	3.50	0.24 to 0.375	0.107	Not ICE CMC model results.

TABLE 2.4 Approximate Total Embodied Energy and Carbon in Building Materials (*continued*)

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC - $kgCO_2e/kg$	EE = Embodied Energy EC = Embodied Carbon
Glass				
Primary Glass	15.00	0.86	0.91	Includes process CO_2 emissions from primary glass manufacture.
Secondary Glass	11.50	0.55	0.59	
Toughened	23.50	1.27	1.35	Only three data sources
Insulation				
General Insulation	45.00	1.86		Estimated from typical market shares. Feedstock Energy 16.5 MJ/kg
Cellular Glass	27.00			
Cellulose	0.94 to 3.3			
Cork	4.00	0.19		
Fiberglass (Glasswool)	28.00	1.35		Poor data difficult to select appropriate value
Mineral Wool	16.60	1.20	1.28	
Paper Wool	20.17	0.63		
Polystyrene	See Plastics	See Plastics		See Plastics
Polyurethane	See Plastics	See Plastics		See Plastics
Rockwool	16.80	1.05	1.12	Cradle to Grave
Woodwool (Loose)	10.80			
Woodwool (Board)	20.00	0.98		
Wool (Recycled)	20.90			
Linoleum	25.00	1.21		Data difficult to select, large data range.
Paint				
General	70.00			Large variations in data, especially for embodied carbon. Includes feedstock energy. Water based paints have a 70% market share. Water based paint has a lower embodied energy than solvent based paint.
EXAMPLE: Single Coat	10.50 MJ/Sqm	0.36 $kgCO_2$/Sqm	0.44	Assuming 6.66 Sqm Coverage per kg
EXAMPLE: Double Coat	21.00 MJ/Sqm	0.73 $kgCO_2$/Sqm	0.87	Assuming 3.33 Sqm Coverage per kg
Plaster				
General (Gypsum)	1.80	0.12	0.13	Problems selecting good value, inconsistent figures, West et al. believe this is because of past aggregation of EE with cement
Plastics				
General	80.50	2.73	3.31	35.6 MJ/kg Feedstock Energy (Included). Determined by the average use of each type of plastic used in the European construction industry.
ABS	95.30	3.05	3.76	48.6 MJ/kg Feedstock Energy
PVC General	77.20	2.61	3.10	28.1 MJ/kg Feedstock Energy. Based on market average consumption of types of PVC in the European construction industry
PVC Pipe	67.50	2.56	3.23	24.4 MJ/kg Feedstock Energy. If biomass benefits are included the CO_2 may reduce to 2.51 $kgCO_2/kg$, and GWP down to 3.23 kg CO_2e/kg.

TABLE 2.4 Approximate Total Embodied Energy and Carbon in Building Materials (*continued*)

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO_2/kg	EC - kgCO_2e/kg	EE = Embodied Energy EC = Embodied Carbon
Sealants and Adhesives				
Epoxide Resin	137.00	5.70		42.6 MJ/kg Feedstock Energy (Included). Source: www.plasticseurope.org
Mastic Sealant	62 to 200			
Soil				
General (Rammed)	0.45	0.023	0.024	
Steel				
General - UK (EU) Average Recycled Content	20.10	1.37	1.46	EU 3-average recycled content of 59%. Estimated from UK's consumption mixture of types of steel (excluding stainless). All data doesn't include the final cutting of the steel products to the specified dimensions or further fabrication activities. Estimated from World Steel Association (Worldsteel) LCA data.
Virgin	35.40	2.71	2.89	
Recycled	9.40	0.44	0.47	Could not collect strong statistics on consumption mix of recycled steel.
Timber				
Note: These values were difficult to estimate because timber has high data variability. These values exclude the energy content of the wooden product (the Calorific Value (CV) from burning). The embodied carbon emissions are derived from fossil fuels (foss) and biomass (bio). The two numbers together give the total carbon released together if the biomass cannot be considered to be carbon neutral (i.e. if the timber is not from a sustainably managed forest). If the timber is from a sustainably managed forest it is easier to justify the carbon neutrality of burning biomass fuels. In this case the embodied carbon may be taken as the fossil fuel derived carbon only (the first carbon number).				
General	10.00	0.30fos+0.41bio	0.31fos+0.41bio	Estimated from UK consumption mixture of timber products in 2007 (Timber Trade Federation statistics). Includes 4.3 MJ bio-energy. All values do not include the CV of timber product and exclude carbon storage.
Glue Laminated Timber	12.00	0.39fos+0.45bio	0.42fos+0.45bio	Includes 4.9 MJ bio-energy
Hardboard	16.00	0.54fos+0.51bio	0.58fos+0.51bio	Hardboard is a type of fiberboard with a density above 800 kg/m^3. Includes 5.6 MJ bio-energy
MDF	11.00	0.37fos+0.35bio	0.39fos+0.35bio	Wide density range (350–800 kg/m3). Includes 3.8 MJ bio-energy
Oriented Strand Board (OSB)	15.00	0.42fos+0.54bio	0.45fos+0.54bio	Includes 5.9 MJ bio-energy
Plywood	15.00	0.42fos+0.65bio	0.45fos+0.65bio	Includes 7.1 MJ bio-energy.
Vinyl Flooring				
General	68.60	2.61	3.19	23.58 MJ/kg Feedstock Energy (Included), Same value as PVC calendered sheet.
Vinyl Composite Tiles (VCT)	13.70			
Miscellaneous (No material profiles)				
PV Modules	MJ/sqm	Kg CO_2/sqm		
Monocrystalline	4750 (2590 to 8640)	242 (132 to 440)		Embodied carbon estimated from typical UK industrial fuel mix. This is not an ideal method.
Polycrystalline	4070 (1945 to 5660)	208 (99 to 289)		

TABLE 2.4 Approximate Total Embodied Energy and Carbon in Building Materials (*continued*)

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC - $kgCO_2e/kg$	EE = Embodied Energy EC = Embodied Carbon
Thin Film	1305 (775 to 1805)	67 (40 to 92)		
Windows	MJ per Window			
1.2m × 1.2m Single Glazed Timber Framed Unit	286	14.6		Embodied carbon estimated from typical UK industrial fuel mix
1.2m × 1.2m Double Glazed (Air or Argon Filled):				
Aluminium Framed	5470	279		
PVC Framed	2150 to 2470	110 to 126		
Aluminium -Clad Timber Framed	950 to 1460	48 to 75		
Timber Framed	230 to 490	12 to 25		
Krypton Filled Add:	510	26		
Xenon Filled Add:	4500	229		

[a]Excerpted from the *Bath Inventory of Carbon and Energy (ICE)* v2.0, an extensive database of embodied energy and carbon of building materials. The database provides details of references so users can check original sources. (Hammond and Jones, 2008, 2011; used with permission.)

quantities of electricity in the refining process. Cheap electricity (as in the Pacific Northwest, with its once-surplus hydropower) attracts bauxite that is mined thousands of miles away. Aluminum ingots are formed at the smelter, then they are shipped—again, sometimes thousands of miles—to factories that make products such as siding; the products are then transported to a construction site. For a given surface area of finished siding, the aluminum alternative represents about 100 times as much embodied energy as the wood. This, however, is not the end of the story—a designer must consider the impacts of these two siding materials on building energy consumption and envelope maintenance and replacement needs and schedules.

(b) Recycled or Virgin Material

It seems paradoxical that, while the world's population is increasing and its raw materials are decreasing, labor costs are growing so much faster than the costs of raw materials. One consequence is that labor-intensive practices become less economically attractive. Recycling is one such labor-intensive practice, whether at the scale of a household, an office building, or an entire industry.

Building construction, renovation, and demolition involve many opportunities for recycling. Unfortunately, at present, these activities instead are a major source of waste. The U.S. Environmental Protection Agency's 1998 report *Characterization of Building-Related Construction and Demolition Debris in the United States* estimated that 136 million tons per year (123 Mg) of such material are produced in the United States and that 65% to 85% of that total ends up in landfills instead of being reused or recycled (USEPA, 1998).

Consider building demolition. If more of a demolished building could be recycled, more of the energy embodied in its material could be recovered, and fewer virgin materials would be required for some other project. At present, the recovery of usable materials from demolition is limited because the cost of labor is high, and the cost of energy and new products is relatively low. It is currently easier, quicker, and cheaper to reduce a building to rubble and haul it to a landfill than to recycle its components. As landfill capacity becomes scarce, design regulations concerning recycled materials use can be expected.

An Atlantic City, New Jersey, project was able to recycle 90% of its demolition waste. Of a total of 1583 tons (1400 Mg) of demolition waste, only 152 tons (140 Mg) were nonrecyclable. Concrete and masonry became crushed aggregate for road building. Glass became "glasphalt" embedded in road surfaces as reflectors. Wood waste became mulch. At Fort Ord in California, four buildings totaling about 11,000 ft^2 (1022 m^2) were dismantled rather than being demolished, saving roofing boards, framing lumber, and tongue-and-groove wood flooring. Unpainted drywall was reclaimed for composting.

Construction recycling opportunities include crushed wallboard as a replacement for lime in agriculture, carpet ground up for use as attic insulation, plate glass crushed for use in manufacturing glass fiber insulation, and pulverized wood as a composting aid at sewage sludge treatment facilities. Old acoustic ceiling tiles can become part of the slurry from which new acoustic tiles are made. Building materials are now increasingly being made from recycled materials: reinforcing bars from ferrous scrap metal; cellulose insulation from newsprint; parking lot bumper strips, fence posts, and park benches from recycled plastics; and nonstructural concrete from incinerator ash. Even plastic yogurt containers, complete with scraps of aluminum foil, are made into a terrazzo-like floor tile.

Architect Pliny Fisk, codirector of the Austin, Texas–based Center for Maximum Potential Building Systems, has developed a wide array of such applications. His "Advanced Green Builder" home near Austin displays several applications of "ashcrete," made with coal fly ash and bottom ash, producing a 97% recycled-content concrete. This is used as ferro-cement for columns and beams and is foamed for hollow wall infill. Numerous other innovative recycled-material applications are showcased in the home.

The most effective form of recycling involves reuse of a building or building shell. The next most effective form of recycling involves the reuse of a building component as is. A residential demolition-by-hand salvage project in Portland, Oregon, recovered doors, windows, bathroom fixtures, framing lumber, plywood, siding, flooring, and bricks. The energy and economic summary for this project is shown in Table 2.5. Several of the green building certifications (LEED and the Living Building Challenge) value reuse of buildings and materials.

As with water and renewable energy sources, much of the current interest in lowering the embodied energy content of construction materials and increasing the recycling and reuse of products is attributable to green building design efforts. The role of LEED in promoting a change in thinking about materials is outlined in Appendix H. The impact of building materials on occupant health and well-being is also an evolving area of concern and interest. There is a direct link between the selection and maintenance of building materials and indoor air quality (see Chapter 5).

Although no building should provide an unhealthy environment for its occupants, the term "healthy building" is generally used to denote a

TABLE 2.5 Residential Salvage for Reuse

	Embodied Energy[a] Btu/ft^2 Floor Area (kJ/m^2 Floor Area)	Value U.S. \$/ft^2 Floor Area (U.S. \$/m^2 Floor Area)
Total for reusable salvage[b]	46,890 (532,497)	4.90 (52.74)
Demolition energy consumed[c]	–3,380 (–38,384)	
Value of energy embodied in salvage[d]		+0.50 (5.38)
Value of avoided dumping fees		+2.70 (29.06)
Total energy savings and value	43,510 (494,112)	8.10 (87.19)

Source: Joslin et al. (1993).

[a]Based on Stein et al. (1981).

[b]Framing lumber alone constituted 38% of this embodied energy.

[c]Gasoline for transportation and hauling, plus human labor at 254.6 Btu/h (268.6 kJ/h).

[d]Assumed at \$.04/kWh, a very low rate typical of the Pacific Northwest.

building that provides exemplary interior conditions for users with serious allergy (or other) conditions that are exacerbated by indoor pollutants. A discussion of these types of buildings is beyond the scope of this book, but there are several readily available texts that can provide fundamental information on design for healthy buildings. Many building products with substantially reduced heath impacts have been developed and marketed during the past decade.

2.5 DESIGN CHALLENGES

The buildings we design today are very likely, over their lifetimes, to experience major changes in the way they are used and in their sources of energy. The societal value of water and embodied materials will also change. The perspective on resources of future generations is highly unlikely to be that which we hold today. This poses some intriguing challenges for the architectural and engineering professions.

(a) Design for Building Recycling

Designing for the recycling of buildings is a two-part balancing act. First, the designer should provide enough flexibility to prolong the useful life of a building by enabling it to adapt easily to changed usage. Flexibility, however, can be expensive to implement physically and can result in a bland "sameness" throughout a building. The latter characteristic is easier for the designer to change than the former. Second, the design can allow for demounting of parts so that the structure can remain safely intact while reusable materials and components are removed. This, however, can result in heavier buildings in which floor systems are not structurally integrated with beams. This approach also discourages integration of mechanical and structural systems. Furthermore, a demountable building may be especially subject to energy leaks, such as from cracks around self-contained components of the façade.

Some initial guidelines for recyclable buildings are as follows:

1. Design the structure to be separable from everything else and to be easily disassembled. Extensive remodeling is then possible without major structural modifications, and at the end of a building's life, elements of its structure can be reused elsewhere.
2. Design for "breathing room" where possible: between a building and its neighbors or between major spaces within a building. Some expansion is thus possible without relocation. This could include designing the columns and footings to support an extra floor or two for vertical expansion.
3. Maximize the use of on-site (natural) forces such as sun and wind. The less sophisticated the mechanical and electrical equipment, the less obvious will be the obsolescence of such equipment with the passing of time.
4. Use materials and components distinctly: avoid combinations that make recycling of these elements difficult. A steel or plastic pipe embedded in a concrete slab is neither easily repaired nor easily recycled; some assembly "sandwiches" (manufactured building panels) do not allow constituent metals, plastics, and other components to be separated for reuse at the end of the panel's life.

Although maximum savings of embodied energy can be realized when a building component is reused as is, even a "downuse" of building materials will save energy and resources compared to manufacturing from virgin materials.

(b) Design for Energy Transition

Two more challenges to designers arise:

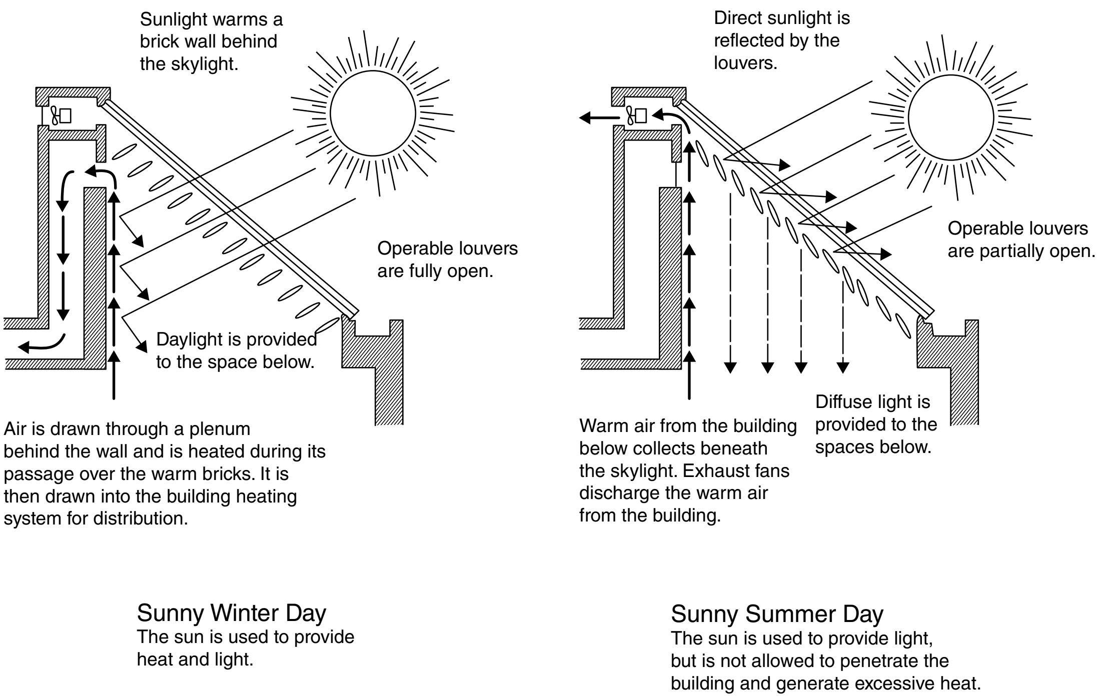
1. *To design buildings not only to save energy, but also so that they can eventually be weaned away from dependence on nonrenewable fuels.* A transition away from electricity from the utility grid, to site-generated photovoltaic or fuel-cell electricity, seems easy enough given planning for appropriate building orientation, collection surfaces, and/or equipment spaces.
2. *To use energy wisely.* This means expecting only a fair share of locally available renewable resources, recognizing that such resources are limited even though they are continuously available. For example, in a high-density setting, it may be tempting to erect a large solar collector to intercept sunlight that would otherwise be utilized by a neighboring building. This temptation grows stronger as a building is designed to rely more heavily upon the sun. The concept of a *solar envelope* to protect each building's fair share is discussed in the next chapter.

(c) Design for the Information Age

Controls for mechanical and electrical systems have become increasingly sophisticated, thanks to developments in information systems and electronics. With the advent of *smart houses*, *intelligent buildings*, and *smart appliances*, it is now possible to regulate an array of building systems collectively and across great distances to optimize performance and minimize resource consumption. For a building with some zones requiring heating and other zones cooling, some zones with available daylight and others without, an automatic central control system can, without human intervention, integrate the flow of fresh air, radiation through movable shading devices, and intensity of electric lighting to achieve maximum use of on-site renewable energy.

The Albany County Airport in New York State uses automated controls to regulate solar gain through a large central skylight (Fig. 2.7). A computer monitors indoor and outdoor temperatures, keeps track of solar altitude and azimuth, and then regulates the insulated shading louver position according to the building's heating or cooling needs. Solar gain is stored in a masonry wall that supports the skylight. A plenum behind the wall then heats air to be supplied to the vestibule areas of the airport, where winter heat losses

(a)



(b)

Interactive Animation

Fig. 2.7 *The Albany County (New York) Airport features a central skylight (a) that provides 40% of the light and 20% of the heat for the building. (b) The insulated louvers are computer controlled to admit or block the sun and to store heat within the building on winter nights. (Courtesy of Einhorn Yaffee Prescott, Architects, Albany, NY. Redrawn by Amanda Clegg.)*

are greatest. Photoelectric controls turn off electric lighting when daylight is adequate. The skylight provides 40% of the lighting and 20% of the heating needs of this 57,000 ft^2 (5295 m^2) building.

Information-rich control systems promise enormous energy conservation achievements while using very small amounts of energy themselves. They also require one of the least space-consuming distribution systems, or *distribution trees*, of all building service systems, especially compared to air ducts and plumbing pipes. In return for such positive characteristics, building designers must recognize that developments in information technology are so rapid that the nature of these systems is likely to undergo frequent and dramatic change. Information system distribution spaces may be quite small, but they must be highly accessible. Where information can be transmitted without wires or cables, the impact on building service space demands is even smaller. Adaptable information systems can make more feasible the renovation, rather than demolition, of older buildings for new tenants. These potentials notwithstanding, the opportunity for occupants to play an active role in the use and control of their environments should not be ignored. In addition, the need to secure computerized controls against malicious hacking must be considered.

(d) Design for Transportation

There are clearly links among design decisions at regional and neighborhood scales (urban planning and subdivision design), transportation, and resulting energy use for commuting, shopping, and recreation. This scale of design, however, is beyond the scope of this book. The link between transportation systems and building mechanical/electrical equipment may seem obscure, but consider the impact on buildings of the automobile and its internal combustion engine. Fresh air intakes at street level face significant pollution from engine exhausts. Parking lots below buildings compete for space with heavy mechanical and electrical equipment such as boilers, chillers, ice storage tanks, and switchgear, and greatly complicate vertical transportation design. Sloped parking floors make future space use for other purposes quite difficult. Ventilating parking levels to remove fumes from automobiles requires large fans and energy to run them.

In a likely future of electrically powered vehicles, photovoltaic arrays over parking areas can provide electricity for a building and recharge the batteries of parked cars throughout the day (Fig. 2.8). In an alternative future of hydrogen fuel

Fig. 2.8 *"Building"-integrated photovoltaics (BIPV) provide shelter, shading, and power for a fueling station/convenience store in Eugene, Oregon. Note the green roof on the store and the biofuel pumps. (Photo by Nathan Majeski.)*

cell–powered vehicles, engine discharge consists simply of water. No fumes are emitted from such cars, saving parking exhaust fan space and energy. To the extent that cars become smaller, or are replaced by public transit or bicycles, significant space may be reclaimed from parking for other uses. When entire buildings are now built as single-purpose parking garages, skillful design for reuse might allow such buildings to be renovated to serve new functions rather than being demolished.

2.6 HOW ARE WE DOING?

From the preceding discussion and that in Chapter 1, it might seem that, environmentally, the building professions are doing pretty well. Minimum standards for energy efficiency and plumbing fixture water consumption are in place that affect virtually every North American building design. Similar standards are also common internationally. There is growing interest in green buildings, generally fueled by private sector and government owners seeking to set an example. This interest is moving the center of gravity of design efforts beyond the just-acceptable minimum requirements of codes and standards. Concern for energy consumption, renewable energy use, water resources and quality, and materials resources and consumption is an integral element of the green building movement. Per capita energy and water use in the United States appears to be stable and/or deceasing.

From the perspective of the previous century, today's building designs (even the worst) are arguably more resource-efficient and respectful of the environment. The question is: From the perspective of tomorrow, is today's good design good enough? The answer in one context is, unfortunately, no. That context is the *environmental footprint*. Environmental footprints are a concept promoted by Rees and Wackernagel (1995) that plots the gross resource demands of a geographic area as a *footprint* on the planet. Figure 2.9 provides an illustration of the environmental footprint concept applied

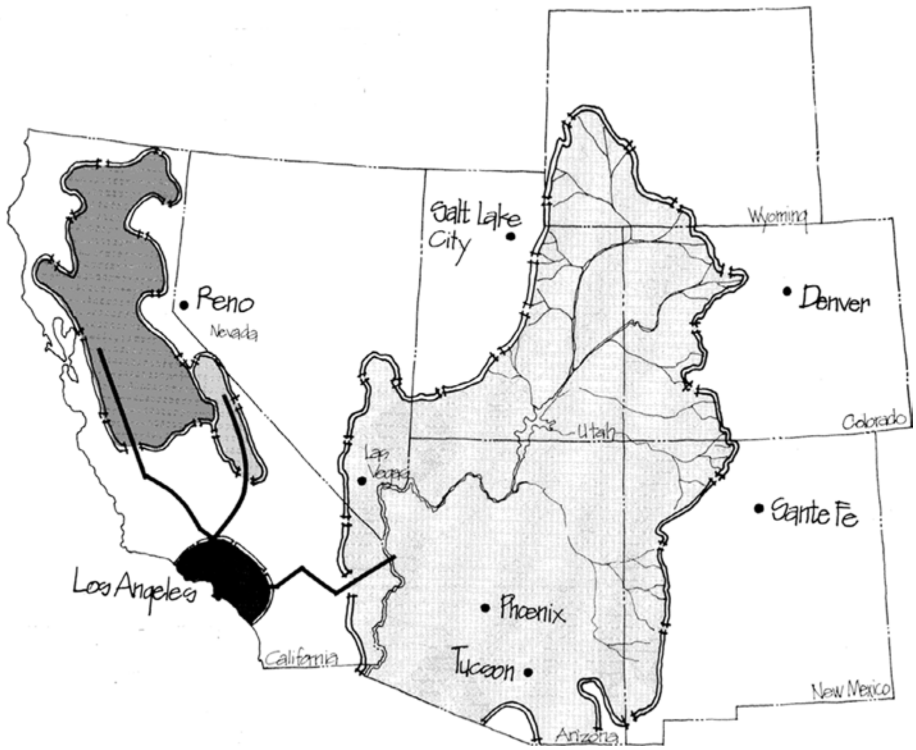


Fig. 2.9 *The effective watershed of the greater Los Angeles area. The area needed to provide water to this metropolitan area (its water footprint) is vastly greater than the politically defined city limits. (From* Design for Human Ecosystems *by John Tillman Lyle. Copyright © 1999 by Harriet Lyle. Reproduced by permission of Island Press, Washington, DC.)*

specifically to water resources. The entity in question may be a city, state/province, or country. If the footprint is larger than the geographic boundaries of the entity in question, then the area is stepping on someone else's environmental toes. Such a city, state/province, or country needs more environmental resources (generally equating to land area) to support itself than are available—thereby surviving through imports from other places. All is well as long as there are other places with surpluses; all is not well when surpluses diminish or disappear. Table 2.6 shows estimated ecological footprints for several countries. It is clear that some countries are substantially overstepping their ecological boundaries, while others are able to help support that overstep because of their less consumptive lifestyle or lower population density. Continuing worldwide population growth, however, makes the footprint balance tenuous. Table 2.7 provides similar environmental benchmarking for the same countries with respect to energy and water use and carbon dioxide (CO_2) emissions. CO_2 is becoming the key environmental metric in the United Kingdom and parts of Europe (Roaf, 2004). Energy appears to be strongly entrenched as the key environmental metric in the United States.

TABLE 2.6 Ecological Footprints for Selected Countries

Country	2007 Population millions	Footprint (gha/pers)	Biocapacity (gha/pers)	Surplus (if +) or Deficit (if –) (gha/pers)
Australia	8.31	6.84	14.71	7.87
Austria	8.31	5.30	3.31	–1.99
Bangladesh	157.75	0.62	0.38	–0.24
Brazil	190.12	2.91	8.98	6.07
Canada	32.95	7.01	14.92	7.91
China	1336.55	2.21	0.98	–1.23
Egypt	80.06	1.66	0.62	–1.04
Germany	82.34	5.08	1.92	–3.16
India	1164.67	0.91	0.51	–0.40
Nepal	28.29	3.56	0.55	–3.01
United Kingdom	61.13	4.89	1.34	–3.55
United States	310	8.00	3.87	–4.13
WORLD	5,892,480,000	2.8	2.1	–0.7

Source: From 2007 data published in the *Global Ecological Footprint Atlas*, by the Global Footprint Network. Data is given in global hectares per person (gha/pers); https://en.wikipedia.org/wiki/List_of_countries_by_ecological_footprint; used under the Creative Commons Attribution-ShareAlike License.

TABLE 2.7 Per Capita Energy[a] and Water[b] Use and CO_2 Emissions[c] for Selected Countries

Country	1997 Population	Energy Use[d]	Water Use[e]	CO_2 Emissions[f]
Australia	18,550,000	5,975	1,250	16.8
Austria	8,053,000	3,790	261	7.9
Bangladesh	125,898,000	145	576	0.2
Brazil	167,046,000	1,064	345	1.8
Canada	30,101,000	8,000	1,494	16.2
China	1,247,315,000	887	494	2.7
Egypt	65,445,000	695	1,013	1.7
Germany	81,845,000	4,264	572	10.2
India	970,230,000	514	635	1.0
United States	268,189,000	7,921	1,682	19.8
WORLD	5,892,480,000	1,631	633	6.1

[a]*Source:* World Resources Institute, Earth Trends: The Environmental Information Portal; http://www.wri.org/resources

[b]*Source:* World Resources Institute, Earth Trends: Formerly found in The Environmental Information Portal.

[c]*Source:* Nationmaster.com; http://www.nationmaster.com/; from World Resources Institute. 2003. *Carbon Emissions from Energy Use and Cement Manufacturing, 1850 to 2000*. Available online through the Climate Analysis Indicators Tool (CAIT) at http://cait.wri.org. Washington, DC: World Resources Institute.

[d]Units are thousand metric tons of oil equivalent per person per year. Data are for 2001. World per capita consumption has been stable over the past 10 years; that of the United States has increased slightly (7538 in 1990; 7921 in 2001).

[e]Units are cubic meters of water withdrawals per person per year. Data are for 2000.

[f]Units are thousand metric tons of carbon dioxide per 1000 people per year. Data appear to be for 2000.

The ecological footprint for the "world" shown in Table 2.6 should lead to serious reflection among those who claim to be producing sustainable design solutions. One unfortunate offspring of the otherwise positive interest in green design is a seemingly endless stream of one-upmanship that glibly promotes "sustainable" this and "sustainable" that—including buildings (virtually impossible in today's economic climate) or communities (possible, but rare today). The term *sustainable* has lost almost any meaning through incessant misuse. This is unfortunate if one believes the story of the ecological footprint—sustainability is essentially keeping the Earth's footprint on the planet. This seems a really good idea, as it is the only planet we have right now.

2.7 CASE STUDY—DESIGN PROCESS AND ENVIRONMENTAL RESOURCES

The Bullitt Center, Seattle, Washington

Project Basics

- Location: Seattle, Washington, USA
- Latitude: 47.6°N; longitude: 47.6°E; elevation: 20 ft (6.1 m)
- Heating degree days: 4908 base 65°F (2727 base 18.3°C); cooling degree days: 2120 base 50°F (1177 base 10°C); annual precipitation: 37 in. (941 mm)
- Building type: New construction; commercial class A office space
- Size: 50,000 ft^2 (4645 m^2); six occupied stories
- Completed: 2013 (Earth Day)
- Client: Bullitt Foundation
- Design team: Miller Hull Partnership, PAE Consulting Engineers (and consultants)

Background. The Bullitt Center in Seattle, Washington, is projected to be the largest commercial building to achieve net-zero energy and water, and will serve as a model for other commercial developments to viably meet future environmental challenges. The Bullitt Center offers competitive market rate class A office space and houses tenants that are leaders in sustainable business and education, such as the Cascadia Region Green Building Council, the International Living Futures Institute, the University of Washington's Integrated Design Laboratory, and the Bullitt Foundation headquarters.

Context. The Bullitt Foundation's mission focuses on sustainable efforts in business, technology, urban issues, ecosystem services and planning, and civic engagement. The vision for the new Bullitt Center is championed by its president, Denis Hayes, to establish a market rate commercial office building in downtown Seattle that produces as much energy as it uses, is a healthy place to work, and can be an educational beacon for progressive planning and ecological design. The Bullitt Foundation planned this through an ambitious process to meet the 2030 Challenge and the Living Building Challenge.

Design Intent. The Bullitt Center serves as a "living laboratory" that visually conveys the benefits of sustainable design and energy efficiency, by engaging users of the building with passive systems. The primary strategy for achieving energy efficiency and water independence was to integrate architectural and engineering designs that focus on a high-quality construction of locally sourced building materials, new technology, and an emphasis on reducing plug loads in the building through energy limits on tenants.

The architecture and building systems of the Bullitt Center were designed to engage occupants so that they consider their consumption of energy. Plate-glass walls display electrical and plumbing equipment, while a generous rooftop photovoltaic array cantilevers well beyond the enclosure, calling attention to the building as shelter from weather and generator of power. The Bullitt Center also provides improved accessibility to walking, biking, and public transit by offering proximity to an adjacent park. The project's ability to become a neighborhood resource led to discussions with the City of Seattle, Department of Parks and Recreation, Seattle Parks Foundation, and neighbors on how to create a vibrant public space adjacent to the Bullitt Center and improve the pedestrian crossing.

Fig. 2.10 *Street facade view of the Bullitt Center, showing stairway, adjacent park, and cantilevering photovoltaic array. (© Benjamin Benschneider/OTTO.)*

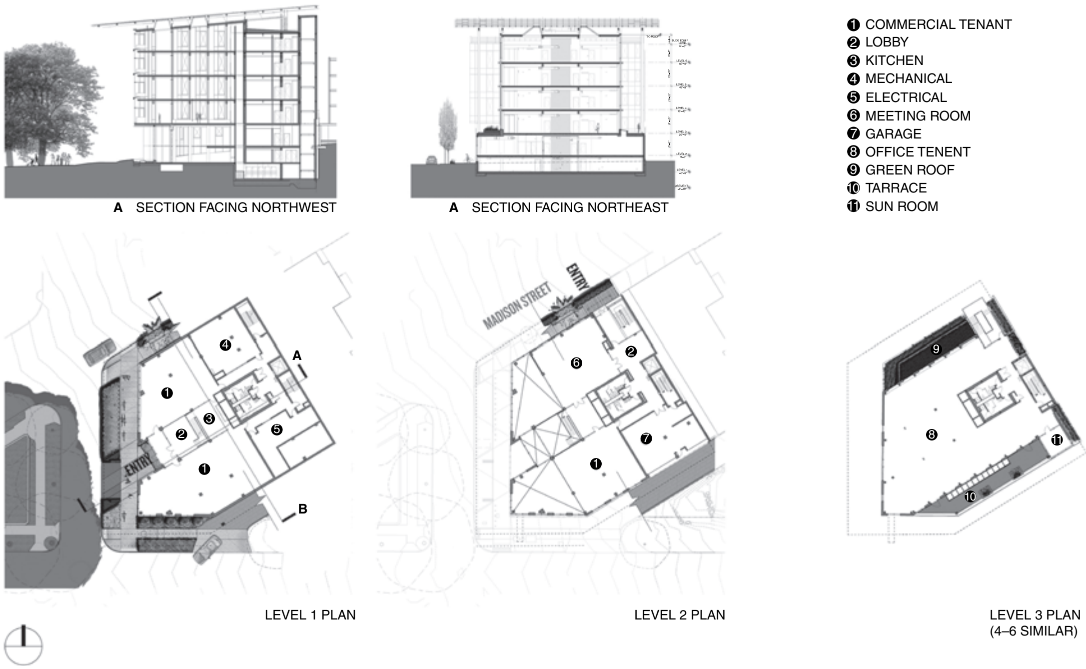


Fig. 2.11 *The Bullitt Center sits on a tight urban site, six stories above grade. (© Miller Hull Partnership; used with permission.)*

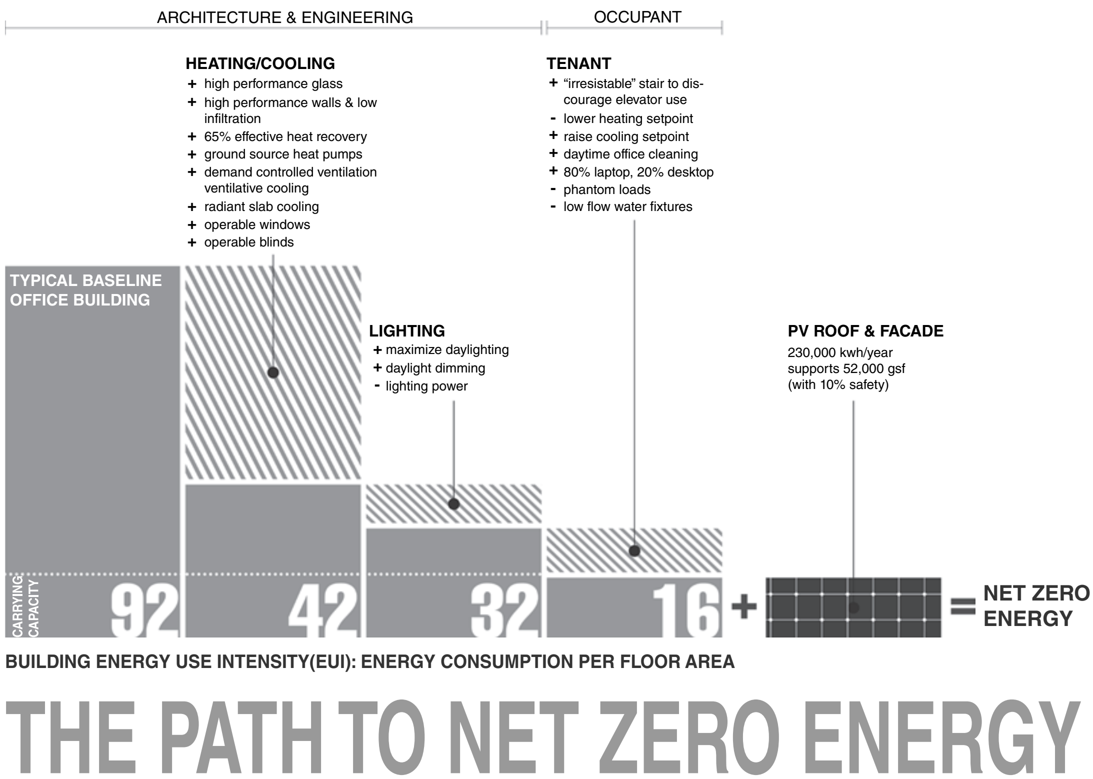


Fig. 2.12 *Path to net-zero energy from a baseline building and load reductions through heating, cooling, lighting, occupants (behavior and tenant contracts), and energy generated on site. (© Miller Hull Partnership; used with permission.)*

Fig. 2.13 *"Irresistible stair" designed to encourage occupant use, is located outside of the thermal envelope. (© Alison Kwok; all rights reserved.)*

Collaboration with the City of Seattle led to a reevaluation of building ordinances that prevent sustainable design. The collaboration led to an initiative called the Living Building Ordinance (No. 123206) that sets a goal of motivating the construction of 12 Living Buildings in the Seattle area over the next three years (www.bullittcenter.org).

Integrated Design Process. The desire for a simple architectural design with integrated building systems required an iterative performance-driven design process on the part of the owners, engineers, architect, contractor, and consultants.

The first step included assembling a team of sustainable design specialists at a two-day workshop that isolated the design problems, criteria, and vision for the project. The Miller Hull Partnership worked with Solar Design Associates to create a schematic drawing that responded to the vision of the project and accommodated the major target of achieving an energy utilization index (EUI) of 20, while generating an estimated 250,000 kWh/yr. Following an exploration of variations on the building massing from that schematic drawing, weekly meetings were held between the architect, engineers, contractor, and subcontractors. The engineers worked closely with the architects and tracked the effects that design changes would have on the energy performance of the building. The design team developed relationships with local contractors who were fabricating and installing high-performance building components such as a curtainwall system designed and engineered in Germany.

Digital tools were used to optimize the systems in the building. The CAD modeling software Rhino combined with Grasshopper (parametric software) was used to quickly analyze iterations of roof forms, and solar panel orientations. The panel power production was estimated with a variety of

Fig. 2.14 *Elevator is located inside of the building and does not draw attention to itself. (© Alison Kwok; all rights reserved.)*

tools and methods. Analysis of daylighting performance was made possible through the use of digital software such as Ecotect and collaboration with the Integrated Design Lab at the University of Washington. PAE Consulting used the thermal and airflow analysis software Bentley Tas v 9.1.4 combined with EQuest energy modeling to analyze how radiant cooling and natural ventilation could further reduce energy loads.

The design of the Bullitt Center engaged education as a way to inspire the construction of future Living Buildings. Architecture studios at the University of Washington both analyzed the proposed designs and designed alternative schemes for the site. Throughout the construction process, students have visited the site to learn about the challenges of designing and constructing a Living Building

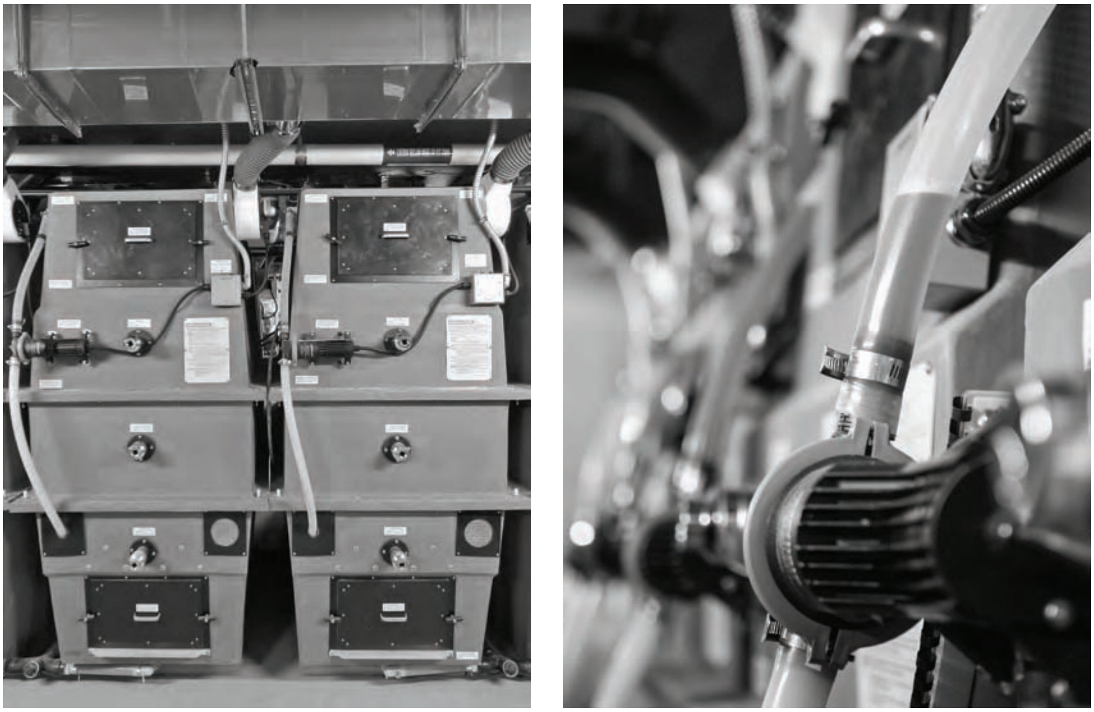
Criteria. The Bullitt Center is seeking Living Building Challenge certification that requires the site and building to provide all of its own power, water, and waste management, in seven categories (termed "petals" in reference to a flower).

1. Site: The building provides amenities for pedestrian, bicycle, and transit access.
2. Water: A concrete cistern under the site stores rainwater for reuse in the building. The system is designed to accommodate all water needs on site. Wastewater is treated on site.
3. Energy: Energy conservation is achieved by the high-performance enclosure, daylighting, and imposed energy budgets for occupants. These measures reduce energy loads to the point where all energy needs can be generated by a solar photovoltaic array on a net annual basis.
4. Health: The inviting stair, access to bike racks, and open floor plan with operable windows and access to daylight motivate a social and active lifestyle.

(*a*)

(*b*)

Fig. 2.15 *(a, b) Tenant space features flexible, open-office plan with shared services at the inner core. (© Alison Kwok; all rights reserved.)*



(*a*) (*b*)

Fig. 2.16 *(a) Phoenix composters (made in Montana) in the basement of the building combine waste from the toilets with wood shavings and a small amount of water, causing aerobic decomposition. (b) Close-up of water and liquid composter. (a) © Alison Kwok; all rights reserved; (b) © Miller Hull Partnership; used with permission.*

Fig. 2.17 *500-gallon (1893 L) "day tank" contains rainwater that has gone through the purification system. The building will only use ~300 gallons (1136 L) per day, so this tank serves as a buffer, since the purification system produces water at about 3–5 gallons (11– 19 L) per minute. (© Alison Kwok; all rights reserved.)*

5. Materials: "Red List" hazardous materials, including PVC, cadmium, lead, mercury, and hormone-mimicking substances are not included in construction, to the maximum extent feasible. All wood is certified to Forest Stewardship Council standards.
6. Equity: The open floor plan of the building and tall floor-to-ceiling widows with operable sashes will provide fresh air and daylight to all occupants.
7. Beauty: Exposed structural timbers, access to views, native trees and shrubs, and a well-crafted building work together to create a comfortable and inspirational work environment.

Key Design Features

Building Massing Orientation. Six stories with 70 ft (21.3 m) deep floor plates and a central service core are surrounded by operable floor-to-ceiling windows that daylight and ventilate the spaces. A glazed "irresistible" stair is situated outside of the conditioned enclosure of the building, serves at the entry to the building, where occupants and visitors are encouraged to take the stairs (rather than the elevator) and enjoys views to downtown Seattle.

Solar Array. A photovoltaic array of 575 panels, each at 425 watts per panel, produces a total of 242 kW under rated conditions and is projected to generate 230,000 kWh in a typical year. A steel frame holds the array, which cantilevers beyond the perimeter of the building. The photovoltaic array shelters a mechanical area on the roof and houses 19 inverters that convert DC power to AC power (http://bullittcenter.org/news/blog/solar-at-the-bullitt-center).

High-Performance Envelope. The enclosure features a triple-glazed curtain wall system that was engineered in Germany but fabricated locally. Super-insulated wall areas are designed to eliminate thermal bridging and greatly reduce air infiltration. The design team took care to select a fluid-applied, weather-resistive air barrier that was produced within 300 miles of the Bullitt Center and did not include any materials from the Red List.

Heating and Cooling. The low levels of heating and cooling required, due to the high-performing envelope, are met with a ground-source heat pump fed by 26 wells; the heating and cooling is provided via piping in the concrete floors. Operable windows both cool and provide fresh air to the building.

Ventilation. An air-to-air heat exchanger, located on the roof and sheltered by the photovoltaic panels, brings in outdoor air that is distributed through the dedicated outdoor air system. When cooling is desired, automated actuators on the windows allow natural ventilation to be the first cooling strategy, and the automation allows for both night and daytime ventilation.

Transportation. Site planning and building circulation feature innovative ideas that elevate the experience of place through the support of access to city transit stops, bike paths, and bike racks. The main circulation stair rewards users with views, convenience, and social interaction. The stairs are made more appealing by a slow elevator that requires key card access.

Water Use and Collection. The project plans to use rainwater to satisfy all of its water needs, including a filtration system that treats rainwater to provide potable water for drinking, cooking, and showers. (Currently Seattle ordinance does not allow the use of rainwater for potable uses.) A 56,000-gallon (211,980 L) rainwater cistern collects water from the roof, while graywater is filtered and recycled for future nonpotable use on the green roof.

Waste Management. Foam-based composting toilets reduce water demand on the site, while anaerobic bacteria process human waste in 10 composting tanks located in the basement.

Long Life Cycle. Life-cycle design considerations include a timber structure that is predicted to last 250 years, a durable 50-year building enclosure, and a photovoltaic array technology that will be competitive for 25 years. Construction costs for the project were 20% higher than comparable types of projects.

Site Sustainability. A green roof, bioswales, and constructed wetland in the adjacent park will filter and treat all water that falls onto the site. Collection, reuse, evapotranspiration, and infiltration of graywater back into the ground will limit the impact that the Bullitt Center has on non-source-point pollution of water that makes its way to Puget Sound.

Reduced Plug Loads. A limit of 0.8 W/ft^2 is set on all office equipment, including computers, copiers, scanners, and the like. Typical office plug loads can be 1.5 W/ft^2 or greater. Occupants will have to select energy-efficient technology to operate within the plug load limit.

Post-Occupancy Evaluation. In compliance with the Living Building Challenge, the Bullitt Foundation will collect detailed performance information regarding energy, water, and waste via monitoring systems for at least one year. These results will be compared with the predicted energy study conducted by PAE Consulting, who created the eQUEST energy model. Monitors that display the building energy use are on view in the lobby of the building.

In 1977, Dennis Hayes wrote, "For rich lands and poor alike, the energy patterns of the past are not prologue to the future" (*Rays of Hope*). When this building opened on Earth Day, April 22, 2013, he said, "If the building is still the highest-performing one of its kind 10 years from now, the experiment will have failed."

Project Data

Projected Energy Report from DOE-2

Predicted Building Energy use for HVAC (heating, cooling, pumping, fans): 3.96 kBtu/ft^2 per year (12.5 kWh/m^2 per year)

Predicted Energy Utilization Index (total building consumption): 16 kBtu/ft^2 per year (50.5 kWh/m^2/yr) (gross floor area); 21 kBtu/ft^2 (66.2 kWh/m^2 per year) (treated floor area)

Awards/Certifications

- First heavy-timber office building in Seattle since the early twentieth century
- First commercial building in the U.S. to earn Project Certification from the Forest Stewardship Council (FSC)
- 2012 Design & Build with FSC Award
- Project Certification: Predicted Living Building certification
- 2011 Eco-Structure: Evergreen Award - On the Boards category
- 2012 AIA Seattle: What Makes it Green Award - Mixed-Use category
- 2012 Forest Stewardship Council (FSC): Designing and Building with FSC Lumber Award
- 2013 Architizer.com: A+ Awards - Special Mention, Architecture and Sustainability categories
- 2013 *Metal Architecture* magazine: Metal Design Awards - Sustainable Design category

For Further Information

The Bullitt Foundation places a high value on making the design, construction, and operations of the Bullitt Center as transparent and accessible as possible. Many reports and analyses are available on the websites of the design team.

The Bullitt Center: http://bullittcenter.org/

Miller Hull Partnership: http://www.millerhull.com/html/nonresidential/Bullitt.htm

Cascadia Green Building Council: http://living-future.org/cascadia

PAE Consulting Engineers: http://www.pae-engineers.com/projects/2012/06/the-bullitt-center/

Hayes, Denis et al. "Bullitt Center Energy Performance." http://bullittcenter.org/learning/ccsdc-energy-performance-report

Elly, Tim. 2011. "The Bullitt Center Bulk Airflow Analysis." Blog, October 4, 2011. http://www.pae-engineers.com/2011/10/04/the-bullitt-center-bulk-airflow-analysis/

Hayes, Denis. 1977. *Rays of Hope*. W. W. Norton & Co, Inc. New York, NY.

References and Resources

American Institute of Architects. 1996. *Environmental Resource Guide.* John Wiley & Sons. [Hoboken, NJ].

Brand, S. 1994. *How Buildings Learn: What Happens after They're Built*. Viking. New York.

Brower, D. 1990. *Cool Energy*. Union of Concerned Scientists. Cambridge, MA.

California Integrated Waste Management Board (recycling in building construction). http://www.ciwmb.ca.gov/WPIE/Building/default.htm

Ewing B., D. Moore, S. Goldfinger, A. Oursler, A. Reed, and M. Wackernagel. 2010. *The Ecological Footprint Atlas 2010*. Global Footprint Network. Oakland, CA.

Fisher, J. 1974. *The Energy Crisis in Perspective*. John Wiley & Sons. Hoboken, NJ.

Hammond, G. P. and C.I. Jones, 2008. "Embodied energy and carbon in construction materials," *Proc. Instn. Civil Engrs.: Energy*, 161 (2): 87–98 [DOI: 10.1680/ener.2008.161.2.87].

Hammond, G.P. and C. I. Jones. 2011. "Embodied Carbon: The Inventory of Carbon and Energy (ICE)." F.Lowrie and P.Tse (eds.), *A BSRIA Guide – BG 10/2011*. BSRIA Ltd. Bracknell, UK [ISBN 978 0 86022 703 8].

Hannon, B., R. Stein, B. Segal, and D. Serber. 1977. *Energy Use for Building Construction*. Center for Advanced Computation, University of Illinois. Champaign-Urbana, IL.

Irurah, D. 1997. "An Embodied Energy Algorithm for Energy Conservation in Building Construction as Applied to South Africa." Ph.D. thesis, University of Pretoria.

UNH. 2004. Watershed Protection, University of New Hampshire: information from website, no longer available

Joslin, J. et al. 1993. *The Waste Papers: Analysis and Discussion of the Potential for Salvage and Re-Use of Construction Materials from Residential Demolition*. Metro Solid Waste Department Publications. Portland, OR.

Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelace, and M. A. Maupin. 2009. *Estimated use of water in the United States in 2005*, Circular 1344. U.S. Geological Survey. http://pubs.usgs.gov/circ/1344/

Lyle Center for Regenerative Studies. http://www.csupomona.edu/~crs/index.html

Lyle, J. T. 1999. *Design for Human Ecosystems: Landscape, Land Use, and Natural Resources*. Island Press. Washington, DC.

Meyers, R. 1983. *Handbook of Energy Technology and Economics*. John Wiley & Sons. Hoboken, NJ.

Redefining Progress. "Ecological Footprint Quiz" (Go ahead, take it.). http://www.myfootprint.org/

Rees, W. and M. Wackernagel. 1995. *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers. Gabriola Island, BC.

Roaf, S. 2004. *Closing the Loop: Benchmarks for Sustainable Buildings*. RIBA Enterprises, Ltd. London.

Stein, R. et al. 1981. *Handbook of Energy Use for Building Construction*. U.S. Department of Energy. Washington, DC.

USDOE. 2012. *2011 Buildings Energy Data Book*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Washington, DC.

U.S. Energy Information Administration. http://www.eia.doe.gov/

U.S. Energy Information Administration. June 2012. *Annual Energy Outlook 2012*, DOE/EIA-0383(2012). USEIA. Washington, DC (online pdf available).

USEPA. 1998. *Characterization of Building-Related Construction and Demolition Debris in the United States*, EPA530-R-98-010. U.S. Environmental Protection Agency. Washington, DC.

USGS. 2009. *Estimated Use of Water in the United States in 2005* (USGS Circular 1268). United States Geological Survey. Washington, DC.

U.S. Geological Survey. "Water Resources of the United States." http://water.usgs.gov/.

CHAPTER 3

Sites and Resources

SITE ANALYSIS SHOULD PRECEDE SITE PLANNING. The purpose of a site analysis is to understand the character of a given site. Such an analysis usually includes the collection of information on climate, solar access, availability of utilities, noise sources, zoning, views, traffic and pedestrian patterns, soil conditions, and the like. In some cases, long-term statistical data are available as an information resource (such as for climate, solar position, utility services); for other variables (such as noise, views, pedestrian density in an urban area) there is usually no existing database, and all information must be collected directly by the designer. To be useful and successful, a site analysis must do more than simply catalog information; it must place value on the collected information in the context of a proposed project and its design intent. For a given building, is solar radiation a desirable resource or a problem to be solved? Is wind a usable design element or an environmental force to be avoided? Understanding what resources are available for inclusion in a design solution, and what natural forces are potential problems to be mitigated by design, is the essence of site analysis—and a necessary precursor to green design.

A designer's early site-planning decisions will, at a later date, influence available options for a building's climate control and lighting systems and affect a building's overall consumption of energy. Site planning must be informed by site analysis. When the site is seen as a collection of resources (sun, wind, water, plants) and also as part of the environment we all share, buildings that greatly reduce dependence upon nonrenewable fuels can be developed. This can be accomplished without limiting the availability of local energy resources for neighboring buildings. In addition to saving energy, the reflective consideration of on-site resources can create outdoor spaces that are especially pleasant to be in. Such spaces can direct winter sun to a glass wall while blocking the wind, or funnel summer breezes through shading to an open window. Site planning is greatly influenced by economic considerations, zoning regulations, and adjacent developments, all of which can interfere with the design of a site to best utilize the sun, the sky, and the wind. Integration of these concerns at the site-planning stage is the first step in adapting a building to its climate. This chapter looks briefly at some aspects of site–climate interactions.

3.1 CLIMATES

Climate is a long-term statistically derived picture of weather. Weather is what happened today or yesterday, while climate has historically been a picture of what happened over the past 10, 15, or 20 years. Our most familiar names for climates describe their most severe season, as shown in Fig. 3.1. This is a convenient means of description,

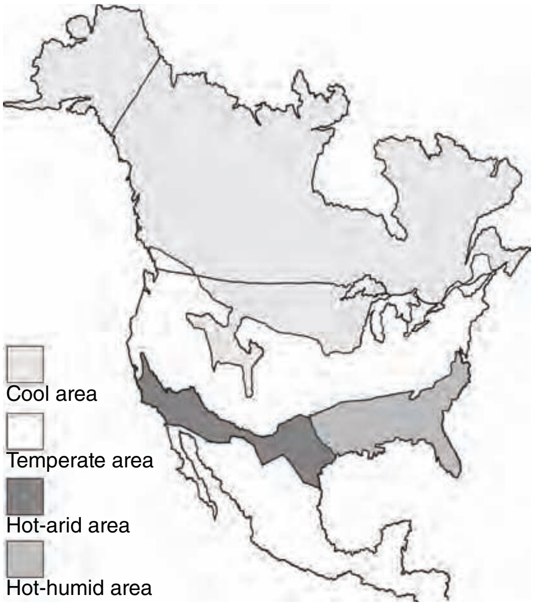


Fig. 3.1 *Regional climate zones of the North American continent. (Redrawn by Tyler Mavichien from: Victor Olgyay,* Design with Climate: Bioclimatic Approach to Architectural Regionalism*; © 1963 by Princeton University Press. Reprinted by permission.)*

but it can be misleading for designers. "Cold" climates can have very hot, sometimes humid, summer days; hot-arid climates can have bitterly cold winter conditions. Before designing buildings that will interact with exterior conditions to provide indoor comfort, we should know in some detail the character of those conditions. This is not necessarily easy, as there are 8760 hours in a year and several climatic variables of interest for each hour (temperature, relative humidity, solar radiation, wind speed, etc.)—and each year is different. A graphical means of portraying these numerous variables is helpful. A very useful set of graphic analysis tools for climates was developed by Olgyay (1963) under the name *bioclimatic design*. Bioclimatic design links comfort and climate. Chapter 4 looks at thermal comfort, but a discussion of Olgyay's approach will provide an introduction to a few key considerations.

Figure 3.2 shows "timetables" developed by Olgyay for cities representative of two of the four climate zones shown in Fig. 3.1. These graphical views of thermal environmental needs are plotted across an entire year (the horizontal axis) for all hours of the day (the vertical axis). Those portions of the year within the bounds of the bold shading line require that a person be shaded to achieve thermal comfort. The darker-colored (overheated) zones are bounded by an isoline that corresponds to a temperature of about 78–82°F (26–28°C), depending upon relative humidity. At higher temperatures, there is a need for air motion as well as shade to remain comfortable outdoors. Areas farther within the overheated zone correspond to thermal comfort needs for 300 and 700 fpm (1.5 and 3.6 m/s) air velocities. An occupancy schedule for a proposed building can be overlaid on such a timetable, providing insights into climate/building/user interactions.

The timetable for New York City (Fig. 3.2*a*) shows that during about one-fifth of the year people require shade for outdoor comfort, with most of the hours from mid-July to mid-August falling in the overheated period. Little relief can be expected at night in summer. Perhaps one-third of the year is "too cold," with temperatures too low for shirt-sleeve comfort outdoors and requiring more than 300 Btu/h ft^2 (960 W/m^2) of radiation, an unlikely solar bounty during New York winters.

The timetable for Miami, Florida (Fig. 3.2*b*), shows that about four-fifths of the year requires shade for outdoor comfort, with about three-fifths falling in the overheated period. During a large portion of the year, people need over 700 fpm (3.6 m/s) wind speed for thermal comfort, with these hours occurring both during the day and at night. There is also a need for wind to counteract high vapor pressure (humidity), independently of high temperature. In Miami wind is clearly important to achieving comfort in any building without mechanical cooling. There is no "too cold" time period in Miami.

The dry bulb hourly and monthly output from Climate Consultant (Fig. 3.2*c, d*) shows similar visual patterns (and dozens of other meaningful displays), produced by a free, graphics-based software program that will accept input for weather stations around the world. Of these two climates, the New York timetable suggests an emphasis on space heating but with a need for cooling as well. In Miami, the focus is upon shading, air motion, and cooling. Several building design strategies can utilize the ambient climate as a source or sink for heating and cooling.

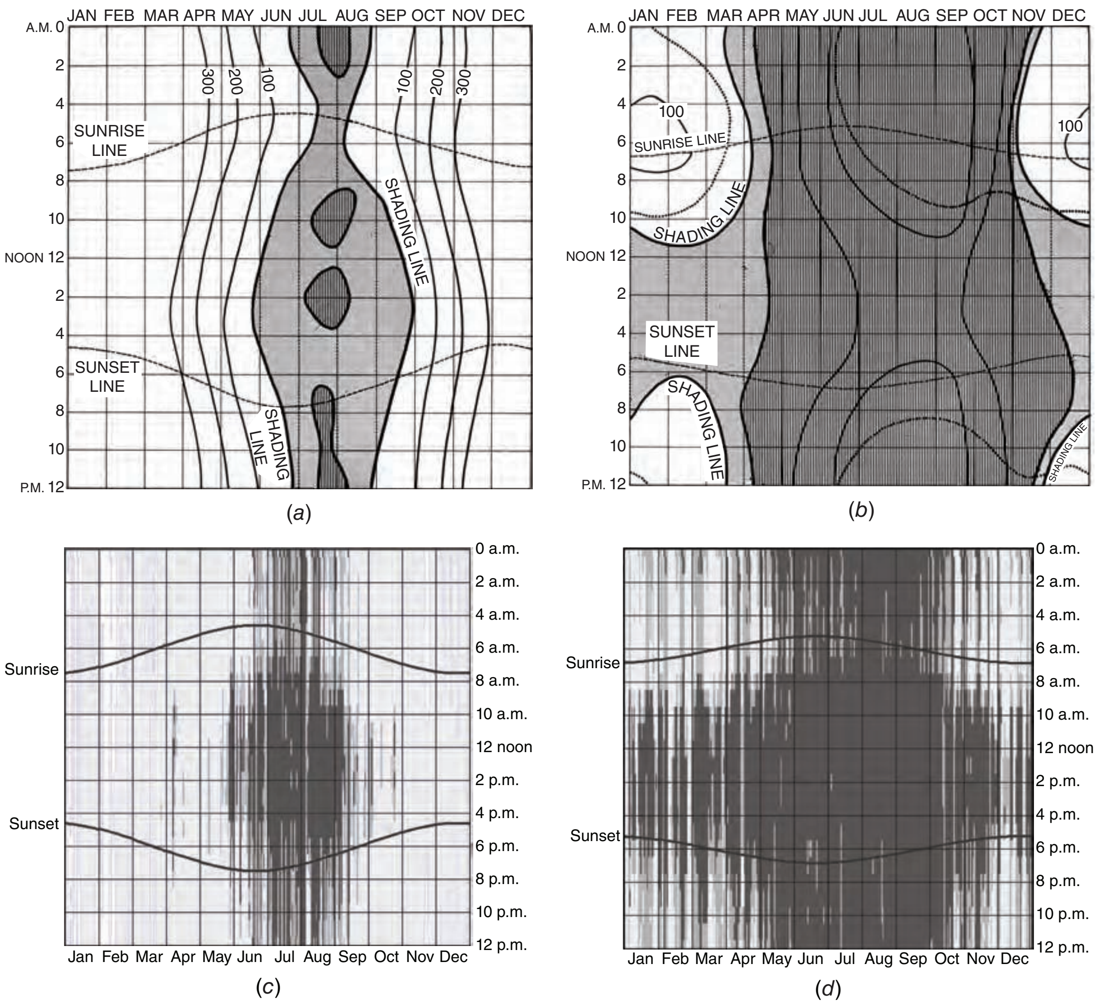


Fig. 3.2 *Timetables of climatic needs for (a) New York City and (b) Miami, cities representative of two of Olgyay's North American regional climate zones. The shaded regions represent overheated zones; the isolines outside of the shaded areas represent solar radiation intensity needed to remain comfortable outdoors without wind. (From Victor Olgyay,* Design with Climate: Bioclimatic Approach to Architectural Regionalism; *© 1963 by Princeton University Press. Reprinted by permission.) Hourly and monthly dry bulb temperature representations of the same cities (c) New York City and (d) Miami using Climate Consultant. The visual patterns and details help the user to characterize the climate more readily than with data tables. (© Climate Consultant 5.0, Regents of the University of California, Energy Design Tools Group, UCLA; used with permission.)*

3.2 CLIMATES WITHIN CLIMATES

The climate at a particular site can be quite different from the nearest available climate data representing a city or region. This is particularly evident when visiting a building site where a neighboring hill blocks wind or winter sun, or an adjacent lake cools summer breezes or adds a damp chill to the winter air. Such local variations constitute microclimates, which have some characteristic distinctly different from the conditions prevailing in the larger macroclimate. The characteristics of a *micro*climate are influenced by the interaction of the site conditions with the *macro*climate:

Site Characteristics	***Climate Characteristics***
Soil type	Solar radiation
Ground surface	Air temperature
Topography	Humidity
Vegetation	Rainfall
Water bodies/flows	Air speed and direction
Views	Air quality
Human effects (heat, noise, etc.)	Snowfall

TABLE 3.1 Average Changes in Climate Effects Caused by Urbanization[a]

Effect	Comparison with Rural Environment
Contaminants	
Condensation nuclei and particulates	10 times more
Gaseous admixtures	5 to 25 times more
Cloudiness	
Cloud cover	5 to 10% more
Fog, winter	100% more
Fog, summer	30% more
Precipitation[b]	
Totals	5 to 10% more
Days with less than 2 in. (5 mm)	10% more
Snowfall	5% less
Relative humidity	
Winter	2% less
Summer	8% less
Solar radiation	
Global	15 to 20% less
Ultraviolet, winter	30% less
Ultraviolet, summer	5% less
Sunshine duration	5 to 15% less
Temperature	
Annual mean	0.9 to 1.8°F (0.5 to 1.0°C) higher
Winter minima (average)	1.8 to 2.6°F (1 to 2°C) higher
Heating degree days	10% fewer
Wind speed	
Annual mean	20 to 30% lower
Extreme gusts	10 to 20% lower
Calms	5 to 20% more

Source: Landsberg (1970).

[a]These effects vary from city to city and from day to day.

[b]Research since 1970 has shown that it is not at all certain that urbanization causes increases in precipitation amount within a city.

Most urban sites are under the influence of an urban subclimate that differs from the conditions of the surrounding countryside unaffected by urbanization. Probably the best-known urban climate feature is the *heat island.* Urban heat island effects are summarized in Table 3.1 and Fig. 3.3. Designers should note that city climatological stations are often located at nonurban sites, such as an outlying airport, masking the effects of a heat island.

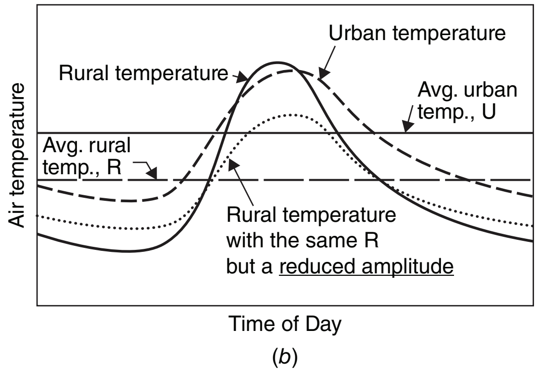
The most obvious reason for a city's relative year-around warmth is its concentration of heat sources: the air conditioner condensers, furnaces, electric lighting in buildings, and internal combustion engines in cars. This urban and industrial heat production is shown in Table 3.2 and Fig. 3.4. It appears that cities and industrial regions of the world release less internal heat per capita as people live and work closer together—although the heat density (temperature) is greater. Commercial and industrial cities release more heat for a given population density, and tropical cities release less, while still conforming to the pattern that greater compactness permits less energy use per capita.

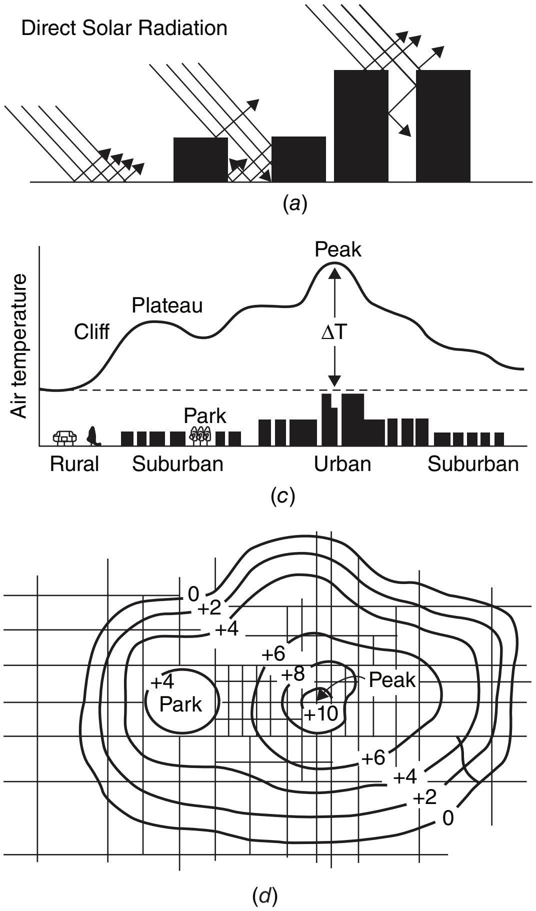
Rain that falls on a city can be an effective evaporative cooling mechanism, especially as water evaporates from wet surfaces. Yet streets and buildings are usually designed to shed water quickly and thoroughly, sending rainwater into storm sewers instead of letting it evaporate slowly in the wind and sun. As a result, evaporative cooling from these surfaces is minimized.

A city also changes the overall cooling action of the wind by channeling it into narrow streets. The geometry of high vertical walls and narrow streets also increases summer heat collection in cities as the high sun is reflected downward to be absorbed and then reradiated by the often rocklike streets and building surfaces. In winter, however, this geometry puts most urban surfaces at a solar disadvantage because the low sun strikes only the upper portion of south-facing walls. A reduction in radiant heat loss at night, caused by this lack of access to the sky, is a key element in the formation of the urban heat island, as summarized in Fig. 3.5. Sky access is discussed in more detail in Section 3.6.

A more subtle urban climate influence is contaminated air. Small particles in a city's air can keep some sunlight from reaching the city, yet can also help to keep the city's heat from radiating outward. These particles also form additional nuclei for fog droplets. Table 3.1 suggests that fog may occur in a city in winter up to twice as often as in the surrounding countryside. Trees and greenery, which can act as crude filters of airborne dust, are not as available in a city.

The city thus modifies its climate from that of its surroundings. In winter, the city's factories, vehicles, surface materials, and geometry combine to increase temperature and reduce the amount of energy needed for heating buildings. The typical means of providing needed winter





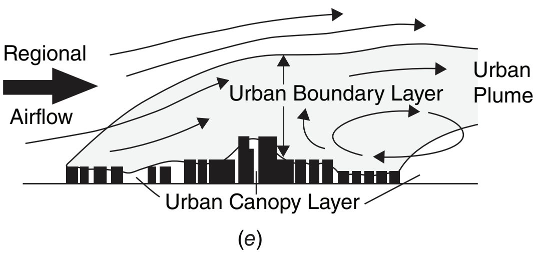


Fig. 3.3 *Urban heat island: a densely occupied area with a temperature distinctly higher than that of the surrounding rural area. (a) Direct solar radiation is likely to be reflected within the city, thereby increasing solar heat gain in urban areas. (b) Temperature records at a rural site (solid line) and in the center of a city (dashed line) during a typical night and day. The city's heat-conducting materials and thin cloud of polluted air acting alone would not change the average air temperature, but would reduce the day–night difference (the dotted line). In addition, the heat from increased solar gain and city-specific heat sources (cars, buildings) warms the air at all hours, producing the observed urban record (dashed line). (c) Idealized profile of the air temperature difference between urban and rural areas at times of peak differences—calm, clear nights. (d) Based upon (c), typical isotherms (lines of equal temperature) provide a "contour map" of the urban heat island. (e) An urban heat island can affect the "downstream" countryside. (Reprinted by permission from Lowry, 1988.)*

heating (fossil fuel–burning heating equipment and power plants) contribute airborne particles and cause urban fog. Solar-assisted heating would diminish this pollution—and with less air pollution, more sun would reach a solar collector. The greater the population density, however, the more difficult is access to winter sun, especially at latitudes farther from the equator, where winter heating is most needed. High buildings readily block low-altitude sun.

In summer, the city's internal heat makes things worse. Air conditioners add their own process heat to the building heat that they pour into the air; their electric load can strain power plants, in turn add more waste heat. Again, solar energy can help, this time through the use of photovoltaic (PV) modules to generate electricity to run the air conditioners. High summer sun angles make solar access much less problematic. The stronger the solar resource, the more electricity will be produced. PV arrays are currently high in first cost, but are noiseless, emit no exhaust gases, and add no internally generated heat to the summer air.

While considering how sun, wind, and other climate elements can be utilized on a site for the benefit of a building's occupants, it is important to remember the need to protect the access of others to these shared resources. In "The Tragedy of the Commons" (1968), Garrett Hardin writes about the commons using the example of

TABLE 3.2 Heat Generated within Cities

City or Region[a]	Population (millions)	Area mile^2 (km^2)	Population Density 10^3/mile^2 (10^3/km^2)	Energy Use per Capita[b] (kW/capita)	Energy Use per Unit Area[b] (W/m^2)
CITIES AND INDUSTRIALIZED REGIONS					
3 Fairbanks[c]	0.045	30.8 (80)	1.6 (0.6)	10.91	6.55
11 Vancouver	0.6	42.8 (111)	14.0 (5.4)	3.55	19.2
12 Brussels	1.3	62.9 (163)	20.7 (8.0)	3.5	28.0
14 West Berlin	2.3	90.7 (235)	25.4 (9.8)	2.14	21.0
9 St. Louis	0.75	96.5 (250)	7.8 (3.0)	5.3	15.9
10 Munich	0.9	116 (300)	7.8 (3.0)	3.0	9.0
5 New Jersey suburbs of NYC	4.7	2355 (6100)	2.1 (0.8)	9.1	7.3
1 Los Angeles County	7.0	3860 (10,000)	0.2 (0.07)	10.5	0.74
4 Nordheim–Westfalen[d]	16.9	13,045 (33,800)	1.3 (0.5)	8.0	4.0
2 BosNyWash[e]	33.0	33,582 (87,000)	1.0 (0.38)	11.2	4.3
COMMERCIAL/INDUSTRIAL CITIES					
15 Sheffield	0.5	18.5 (48)	26.9 (10.4)	1.83	19.0
17 Manhattan	1.7	22.8 (59)	74.6 (28.8)	5.52	159.0
16 Montreal	1.1	30.1 (78)	36.5 (14.1)	7.02	99.0
13 Budapest	1.3	43.6 (113)	29.8 (11.5)	3.74	43.0
8 Cincinnati (summer)	0.6	85.7 (222)	7.0 (2.7)	9.3	25.1
7 Hamburg	1.83	295 (763)	6.2 (2.4)	5.3	12.7
6 Chicago	3.5	711 (1842)	4.9 (1.9)	27.2	51.7
TROPICAL					
18 Hong Kong	3.9	40.5 (105)	96.1 (37.1)	0.88	32.6
19 Singapore	2.1	54.0 (140)	38.9 (15.0)	0.81	12.2

Source: Lowry and Lowry (1995) by permission.

[a]Index numbers refer to Fig. 3.4.

[b]0.317 W/m^2 = 1 Btu/ft^2. These columns were not converted to I-P units. The units shown are as presented in the source, but technically energy should be expressed in kW-h while power is in W.

[c]Data for Fairbanks, Alaska, include a sparsely populated incorporated area surrounding the central business district.

[d]Nordheim–Westfalen is the heavily urbanized and industrialized region in the lower Rhine valley near Düsseldorf–Dortmund.

[e]BosNyWash is the term often used by urbanists to refer to the megalopolis that stretches from Boston through New York to Washington, DC.

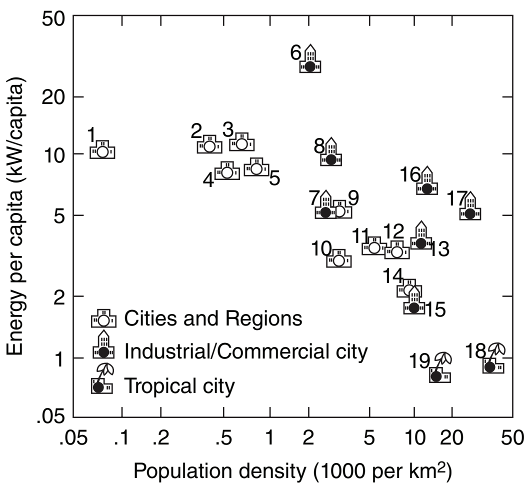


Fig. 3.4 *Population density and energy use per capita for 19 cities and regions. Numbers refer to locations in Table 3.2. The heat island effect is influenced by both density and energy use. (Data with permission from Lowry and Lowry, 1995.)*

publicly owned meadows shared by many herders. Each herder realizes that his personal wealth will increase as animals are added to his herd, so all herders increase their livestock holdings. The carrying capacity of the meadow, however, does not increase; overgrazing occurs, and as a result the commons become unable to support any animals. The following discussions of sun, air, and water resources available on a site are influenced both by the "private" needs of a building and the "public" patterns of resource availability, which should remain accessible to all.

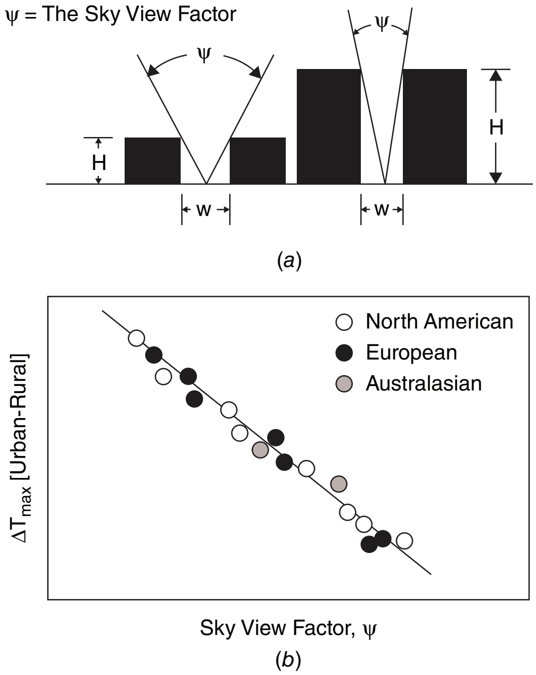


Fig. 3.5 The urban heat island effect is particularly strong on calm, clear nights. (a) With a greatly reduced "sky view factor" (Ψ) to the cold night sky, the walls and floors of urban canyons (the right part of the sketch) cannot lose heat as readily as can the open countryside or less dense suburban areas (the left part of the sketch). (b) The more narrow the Ψ, the more pronounced is the effect (ΔT) of the urban heat island in cities throughout the world. (Reprinted by permission from Lowry, 1988.)

3.3 BUILDINGS AND SITES

Buildings are temporary occupants of their sites. The arrival of a building usually produces rapid and dramatic changes to the biological systems on a site, to the microclimate, and often to the surface geology. Buildings are guests, sites are hosts; a fundamental design question is: How can the two most productively coexist?

A site offers a building earth for support, as a potential heat source and heat sink, and for the growth of plants where building density permits. Sounds on a site depend upon the context, urban or rural. Water is somewhere below a site, flows across it, falls on it as rain, and perhaps collects on its surface. Wind moves erratically across a site. Solar energy arrives in diurnal and seasonal cycles. Long-term patterns of sun, wind, and water are steady and generally predictable, although great variations can occur over shorter (daily, monthly, annual) time spans. At some level, an ecosystem of life is already established (see Fig. 1.1 for Malcolm Wells's take on this web of life).

During the construction process, a building arrives, bringing with it people and vehicles, a flow of materials into and out of the site, sounds of activity, and imported utility services such as electricity, water, and natural gas. The building offers the site electric light by night, a continuous flow of heat (to or from), a radical change in water flows (both at and outside of the building envelope), and liquid and solid wastes (or nutrients, depending upon one's viewpoint). In our society, the waste outflows are most often whisked off for treatment "elsewhere."

When a site is larger than its building, both may be designed to improve building performance and user experiences. Large sites offer smaller buildings the opportunity to accept, filter, or block sun, wind, sound, and rainwater in order to make effective use of on-site resources. Vegetation, ground forms, and orientation, as well as roofs, walls, and floors, can play a role in this interaction.

When a building fills its site, opportunities for on-site resource use are more limited. Because buildings that completely fill sites are often located in densely built-up areas, less usable wind is available around the building walls, and solar radiation may be blocked. The built-upon earth is less able to act as a heat sink or absorb water. The building roof often provides the major opportunity to receive sun and rain, and discharge heat to the environment. It may offer the only opportunity to grow plants on the site. In dense urban areas, the future roofscape will be dominated by climate–building interactions: solar collection, rain collection, heat rejection, water treatment, and gardens. Compared to today's urban roofscape dominated by horizontal black or gray surfaces behind parapet walls, this represents a dramatic design opportunity for aesthetic, social, and technical change. Such a change is already under way in some cities (such as Chicago and Portland, with their green roof initiatives).

3.4 ANALYZING THE SITE

After recognizing the resources that exist on and around a site, a designer can then decide how best to integrate these resources into the building design, while making the building and site a successful addition to the larger patterns of their surroundings. Schematic site plans should be used as an inventory. Diagrams can test design arrangements that relate rooms or functions to their surroundings in the plan view. Sun and wind conditions (in both summer and winter), noise sources, and water runoff patterns are often included in a site analysis plan. It is particularly important to identify microclimates on the site, the places that have special characteristics differing from the regional climate. Microclimates can present opportunities for an expanded comfort zone: more sun in cool periods, more wind in warm periods. Microclimates can sometimes provide building sites where less energy is consumed because the winter is warmer or the summer cooler. Microclimates can also present problem areas to be avoided for buildings or outdoor activity, or where special design measures need to be taken to correct their difficulties.

Microclimates on a site are not limited to those visible on the surface (and presented in plan view). Consequently, both vertical and horizontal site analyses are needed. Conditions of privacy and accessibility, view, heat, light, air motion, sound, and water all change with height above (or below) the surface (Fig. 3.6*a*). To minimize the energy required to construct and operate buildings and to better integrate buildings with their surroundings, programmatic functions should integrate with the characteristics of the most appropriate layer of the site. A lecture hall, requiring an acoustically isolated and closely controlled thermal environment, is an obvious candidate for the subsurface layer. Spaces that will most benefit from views and daylight should occupy levels that best provide such resources.

One building whose form responds to these layers is the Boston City Hall (Fig. 3.6*b*). Activities with the most frequent public interaction are located near the surface, such as the skylit, high-ceilinged lobby, whereas special ceremonial functions are elevated to distinctive forms in the near-surface layer above. The city offices with less frequent public contact occupy several floors in the sky layer, where daylight is plentiful. Storage and mechanical functions, as well as parking, are in the subsurface layer. An aesthetic equivalent of this horizontal layering is architect Louis Sullivan's concept of a façade as a "base, body and capital."

3.5 SITE DESIGN STRATEGIES

Sites can be utilized to assist in heating, lighting, cooling, and noise control for buildings. A range of site strategies were compared with the seasonal roles and effects by Watson and Labs (1983). An extract from this extensive comparison is shown in Fig. 3.7. Several of these strategies are discussed in more detail later in this chapter. The graphics in Fig. 3.7 suggest a focus upon housing but also apply to any occupant situation that can utilize an extended comfort zone.

A house designed by Frank Lloyd Wright in the 1940s (Fig. 3.8) is a great example of how the information in Figs. 3.6 and 3.7 can be skillfully applied in the planning of a building that works with its site. The direct solar heat gain through south-facing windows in winter makes this an early example of *passive solar heating*. (*Active solar heating*, by contrast, includes collector devices and a tank of water or a bed of rocks for heat storage.) This house, known as the Solar Hemicycle, was built in 1948 near Madison, Wisconsin, which lies between the cool and temperate climate zones. Winter heating is the dominant thermal influence in this area. The house stands on a rise in the prairie, particularly vulnerable to winter winds. During construction, earth was scooped from in front of the south face of the house and bermed against the entire curved north wall, almost to roof level. Only a narrow strip of second-floor windows separates the berm from the roof. This berm and curve combination gives winter wind protection from the northeast to northwest and provides further insulation for the north wall. The north wall is made of stone, which absorbs and stores winter solar radiation (heat) that comes in through the floor-to-ceiling, southeast-to-southwest–facing glass. The concrete slab-on-grade first floor also stores solar heat in winter. The impression that this house and site are sun collectors is heightened by an entrance tunnel in the northeast end of the house that leads from the parking area through the berm and onto the sunny, protected south terrace overlooking a sunken "sun-trap" circular lawn. Passage from the cold north side through an even colder tunnel to the sunny south side transitions a visitor into the solar-heated interior.

This house plan is shorter in the north–south and longer in the east–west direction (about a

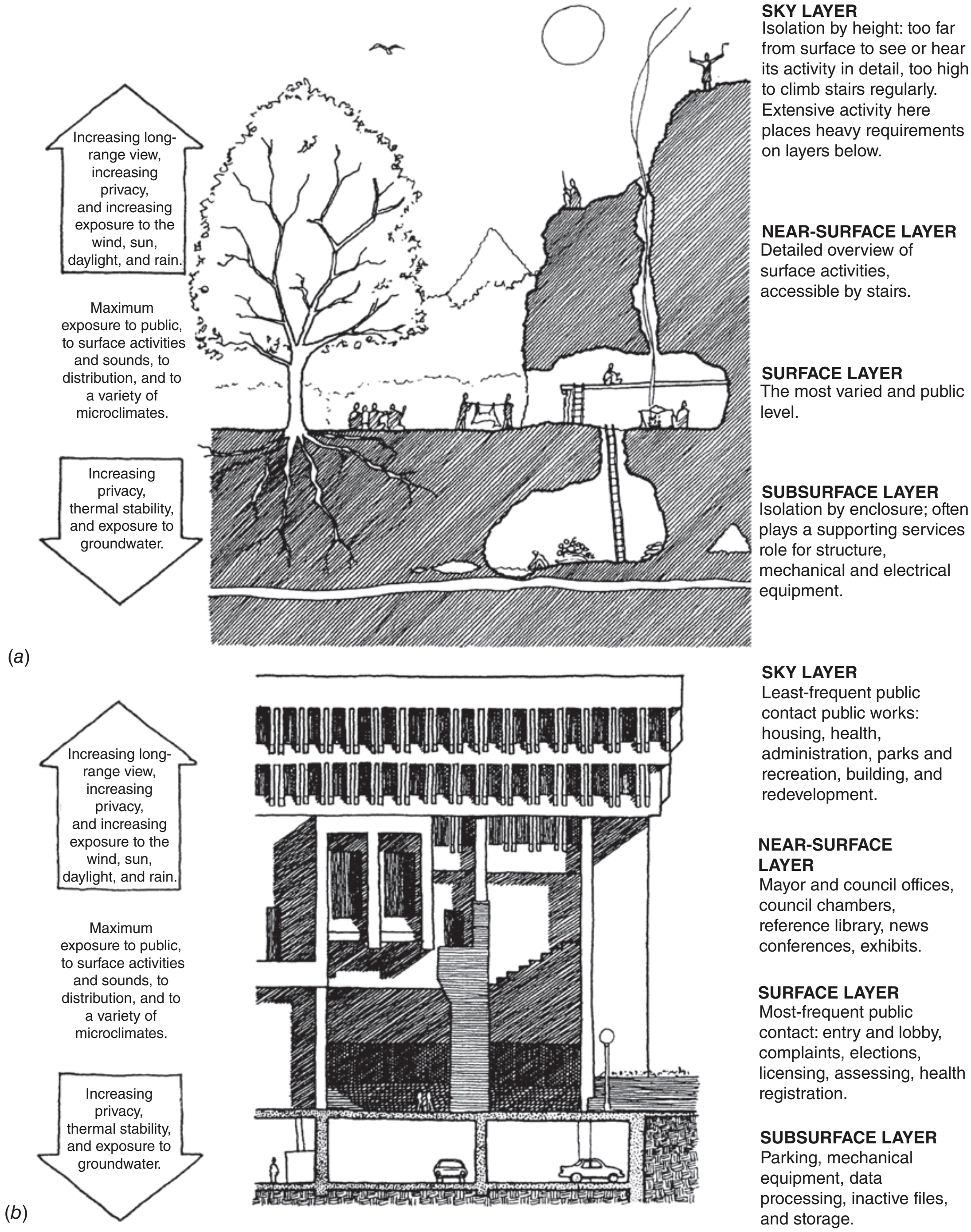


Fig. 3.6 *(a) Characteristics of horizontal layers of a site. (b) Vertical layers and form: Boston City Hall, 1969. (Kallman, McKinnell and Knowles, Architects.)*

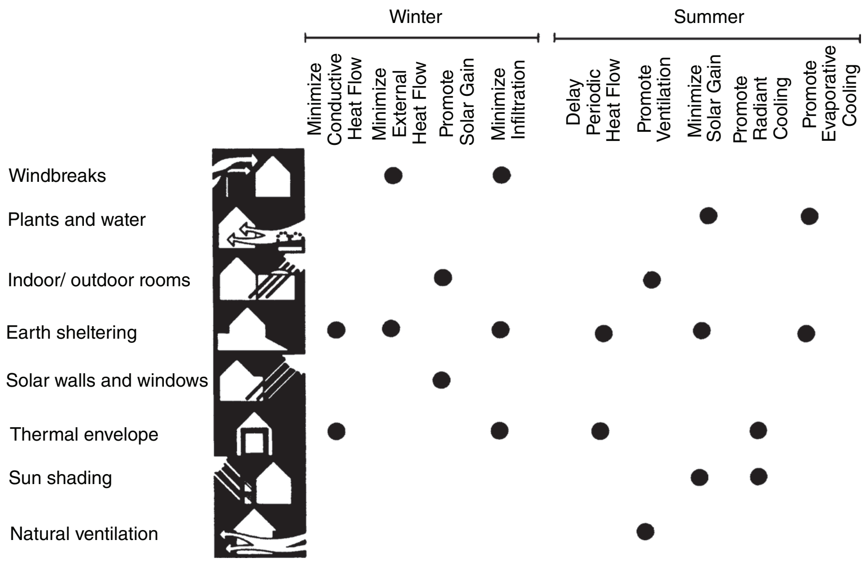


Fig. 3.7 *Generic bioclimatic site design concepts and building strategies. (Reprinted from* Passive Cooling *by permission of the publisher, American Solar Energy Society.)*

1:3 ratio). This elongation is typical of passive solar designs, which are able to store and use winter solar heat gain, and thus profit from having long south-facing glass walls to act as passive collectors. Had these large windows been well insulated at night and the roof and walls insulated to current standards, this house would be a very up-to-date case study of passive solar heating.

In the Solar Hemicycle house, protection from summer overheating is provided by an overhang along the south glass walls, as well as by the shaded and cool thermal mass of the north stone/berm wall combination. The high windows in both the north and south walls allow warm air to rise and escape.

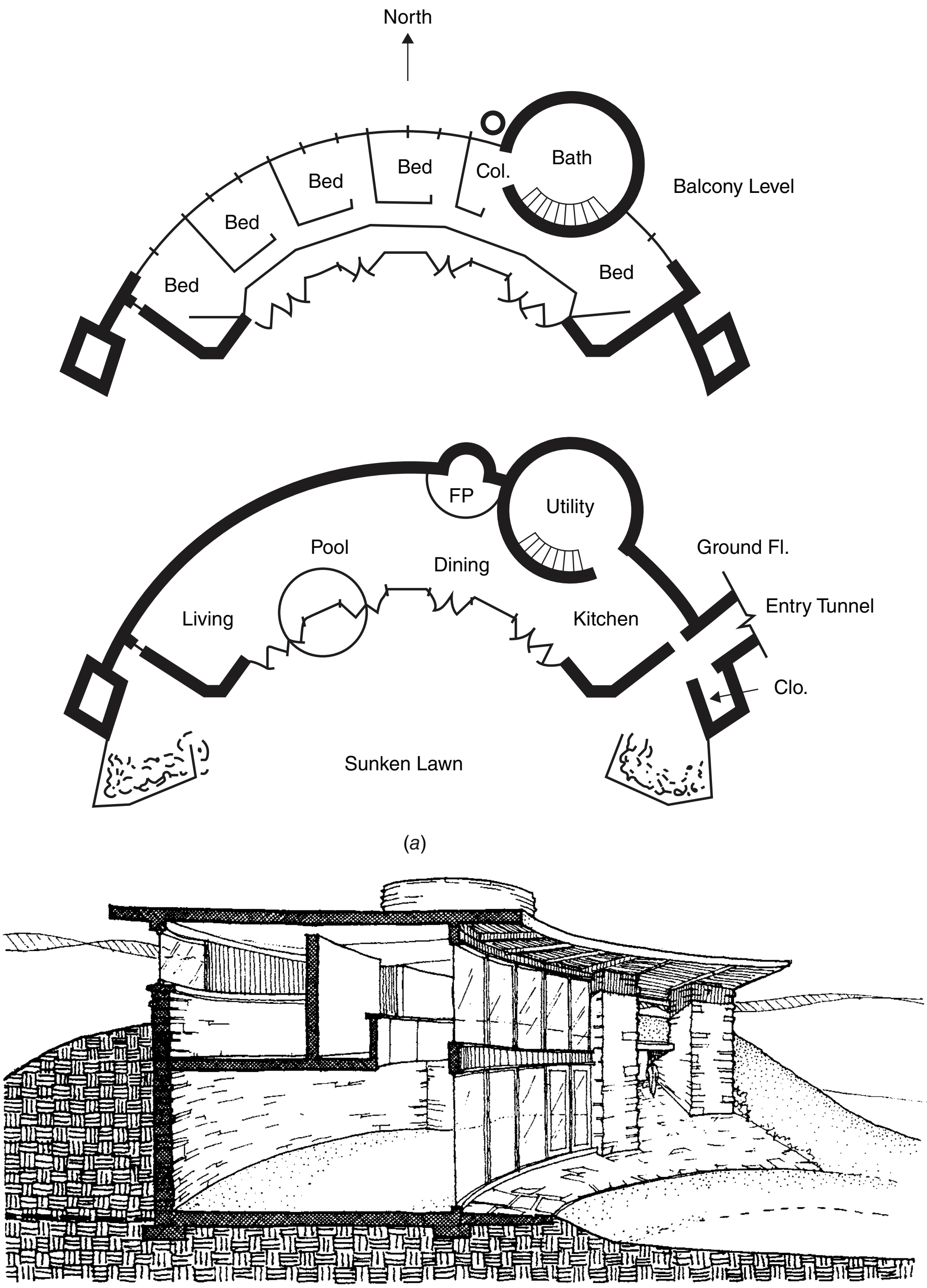
3.6 DIRECT SUN AND DAYLIGHT

The Earth receives only a very small percentage of the sun's daily energy output. This small portion, however, is critically important to life on Earth. Almost all of today's energy sources have the sun as an ancestor. Fossil fuels are solar energy that has been concentrated by time and geologic conversion. Biomass, hydropower, and wind power represent shorter-term concentrations of solar energy. Even without concentration, the renewable solar resource is often more than adequate for building heating and lighting.

The amount of solar energy available at any given site varies both seasonally and daily. Typically, the nearer the sun approaches a position directly above a site, the more solar energy reaches a horizontal surface. Fortunately, solar radiation's embodied heat energy is not its only resource; direct sun is our most intense light source—too intense, in fact, for most building situations. Indirect sunlight, however, as available on an overcast day or from the clear north sky, is a wonderfully diffuse and readily utilized light source.

(a) Access to Light and Sun

The value of daylight (and fresh air) to buildings has long been recognized in zoning laws, which typically require that minimum distances (setbacks) be maintained between a building and the property line in lower-density areas. Height restrictions often accompany these setbacks, defining a maximum buildable volume that a building can fill (Fig. 3.9). As density increases and buildings become taller, daylight is diminished as it reflects down between buildings; in response, the maximum buildable volume becomes narrower as it rises.



(a)

(b)

Fig. 3.8 *An early passive solar-heated home, Frank Lloyd Wright's Solar Hemicycle (Jacobs House II) near Madison, Wisconsin. The house was designed in the early 1940s and built in 1948. (a) Floor plans. (b) Section-perspective, looking east toward the entry tunnel in the berm wall.*

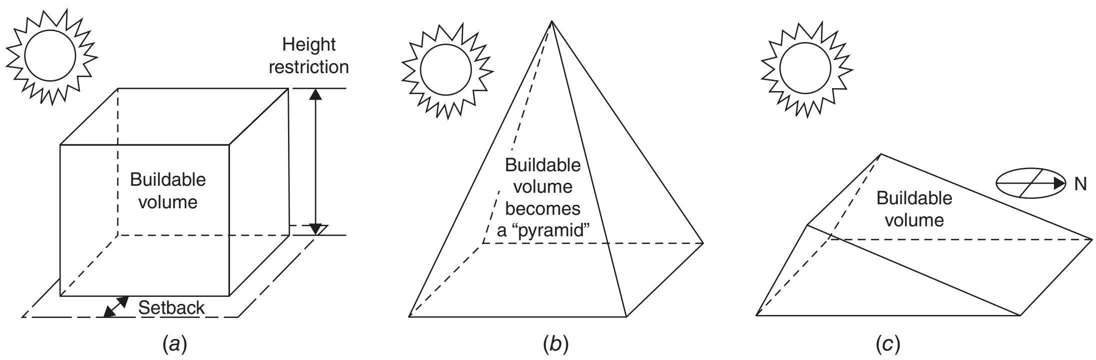


Fig. 3.9 *Protecting access to light and solar radiation. Three regulatory approaches that compromise between private optima (e.g., maximum rentable floor space) and public optima (e.g., daylight at street level). (a) Simple daylight access, residential and low-rise commercial areas. (b) Daylight access in high-density areas. (c) Access to direct sun for winter heating.*

When direct sun in winter is desirable at ground level on all sites, the buildable volume must be sharply reduced in height due to the low angle of the winter sun in northern latitudes. Protection of this most-restricted buildable envelope, called the *solar envelope*, is at present rarely mandated, but a few cities have enacted solar access ordinances for residential zones. The most restrictive feature of the solar envelope is the low slope of its northern face, usually corresponding to the altitude of the sun (angle above the horizontal) for about 2 hours before and after noon on December 21. This feature allows 4 hours of access to direct sun for a neighbor on the site just to the north, on even the shortest day.

A brief history of daylight and solar access regulations and an overview of current design guidelines are given in DeKay (1992). Figure 3.10 shows the application of six variations of regulations on an east–west elongated urban block at 40°N latitude. The east–west streets are wider than the north–south streets. Further development of the solar envelope concept is shown in Figs. 3.11 and 3.12, based upon the work of Knowles (1981). As suggested, maximum density of development is closely related to maintaining winter solar access.

For daylight access, building surfaces can be almost as important as building geometry. The importance of light reflected from vertical and horizontal surfaces is apparent in daylighting analyses. Lighter-colored surfaces result in more daylight, especially in crowded urban conditions, where a view of the sky from windows is not common. An increase in daylight for all surfaces on an urban street will result if the building and site surfaces have light colors. This can conflict with the use of planting for shading and evaporative cooling, although light-hued groundcovers are available. Although daylight diffusely reflected from building and ground surfaces is a potential benefit,

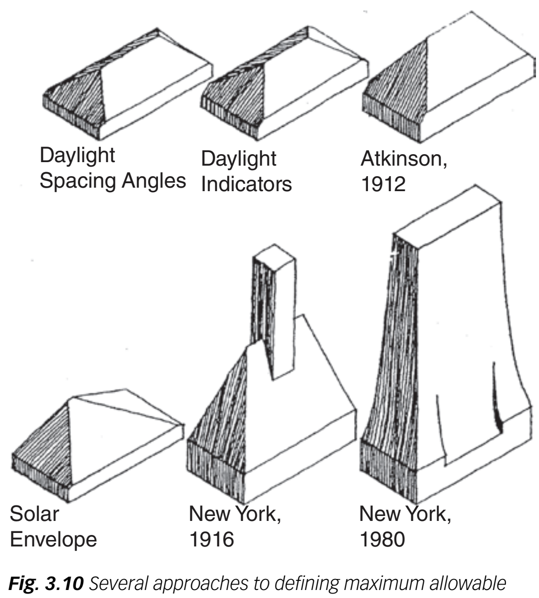
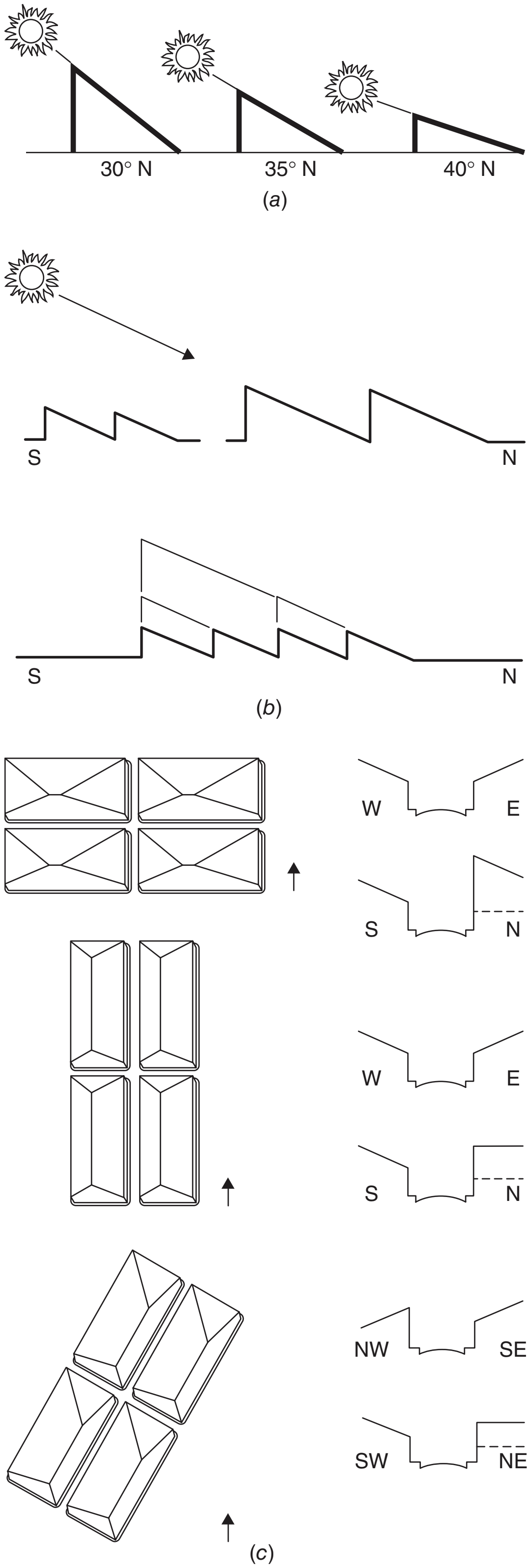


Fig. 3.10 *Several approaches to defining maximum allowable building envelopes for daylight access. These envelopes are applied to a 200-ft × 400-ft (61-m × 122-m) block at 40°N latitude. The east–west streets (along the longer side) are 65 ft (20 m) wide; the north–south streets are 45 ft (14 m) wide. In this case, "daylight spacing angles" and "daylight indicators" produce nearly identical envelopes. (From DeKay, 1992, with permission of the American Solar Energy Society.)*



harsh specular reflections of direct solar radiation from mirror-like surfaces are often unwelcome. See Section 3.6(f).

(b) Charting the Sun

During site analysis, one of the earliest tasks is to determine when direct solar radiation would reach a proposed space—such as a classroom, playground, office, deck, or courtyard—on a site. Information on solar geometry is presented in Chapter 6. Numerical data on sun position and intensity are found in Appendices C and D. Details of how a building can utilize the sun are found in later chapters dealing with solar space heating, solar water heating, and daylighting. Effective design for solar utilization, however, begins with an understanding of the basics.

The chart in Fig. 3.13 shows the sun's position for 40°N latitude and also shows, for the 6 hours of greatest insolation, what percentage of clear-day insolation is gained each hour by an unshaded south-facing vertical window. To convert these percentages to actual heat gains, see the numerous tables in Appendix C with data for *clear* days at a given latitude and the table (showing January and July only) for an *average* day by climate station. The emphasis on a southern orientation (in the Northern hemisphere) calls attention to the useful fact that such an orientation receives *more* sun in winter and *less* sun in summer than any other orientation.

(c) The "Band of Sun"

A building section drawing can be a powerful site analysis tool. As shown in Fig. 3.14, a north–south section can be drawn through a proposed building and its site. For three days of the year (each solstice and the equinox), the solar altitude angle at noon is determined. This allows the *band of sun* that would strike the building and site at the noon altitude to be drawn. The portion of this direct solar radiation

Fig. 3.11 *These solar envelopes are refinements of the solar access "pyramid" of Fig. 3.9. (a) The slope of the solar envelope changes with latitude. (b) The larger the site, the greater the buildable volume of the solar envelope. (c) Solar envelopes for various individual site orientations. (Reprinted, by permission of R. Knowles, from* Sun, Rhythm, Form*; © 1981, MIT Press.)*

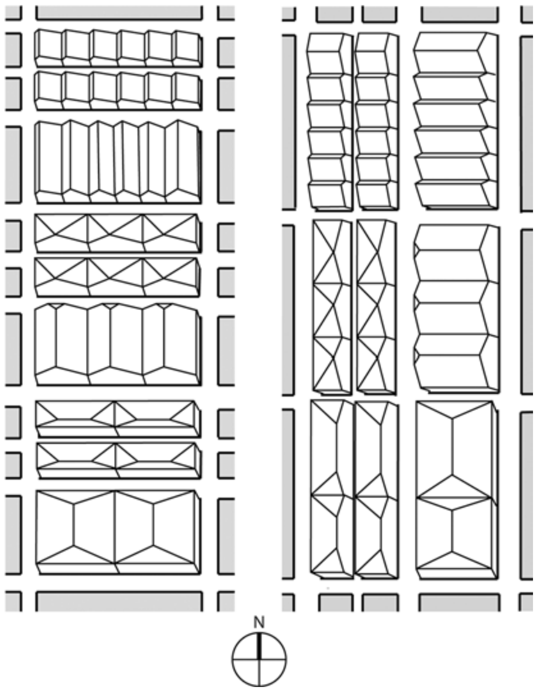


Fig. 3.12 Solar envelopes for east–west elongated blocks (left) and for north–south elongated blocks (right). (Reprinted, by permission of R. Knowles, from Sun, Rhythm, Form*; © 1981, MIT Press. Redrawn by Nathan Majeski.)*

resource that is used by the building and site can be easily visualized. The portion of the band that is unused in each season illustrates the potential for redesign in order to better utilize the solar resource. This analysis helps to show how wintertime solar utilization depends upon lower sun altitudes, and summertime uses depend upon higher altitude angles.

(d) Skylines and Winter Sun

The skyline as actually seen from a given position on a site can be charted to determine access to direct solar radiation at any time of the year (Fig. 3.15). This type of obstruction analysis should precede the placing of any solar collector, whether it is a south-facing window or a manufactured collector (PV or solar thermal). Obstructions within the six "best" collection hours (9:00 A.M. to 3:00 P.M.) are particularly serious and should be minimized when siting a collector.

At the same time, consideration of neighbors' access to direct solar radiation is appropriate. This can be checked by charting the skyline somewhere along the northern boundary of the site. The outline of the proposed building design should be

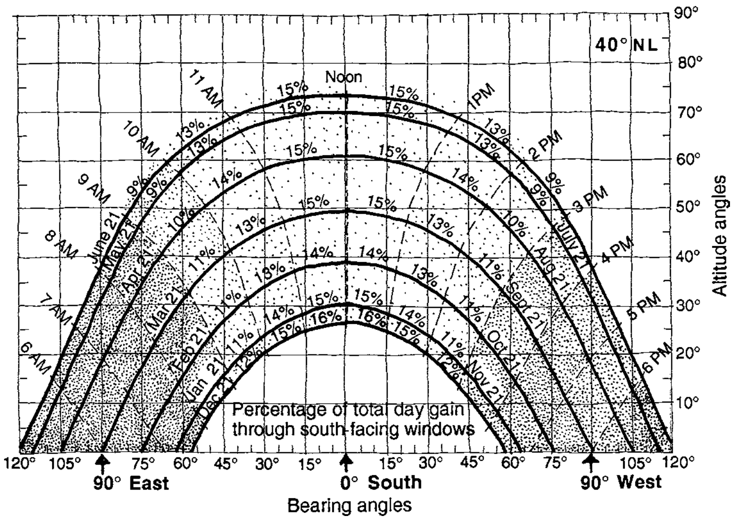
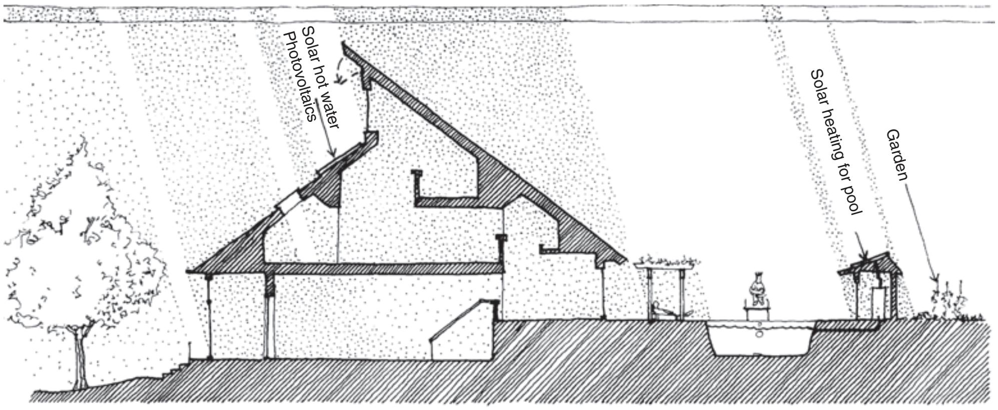
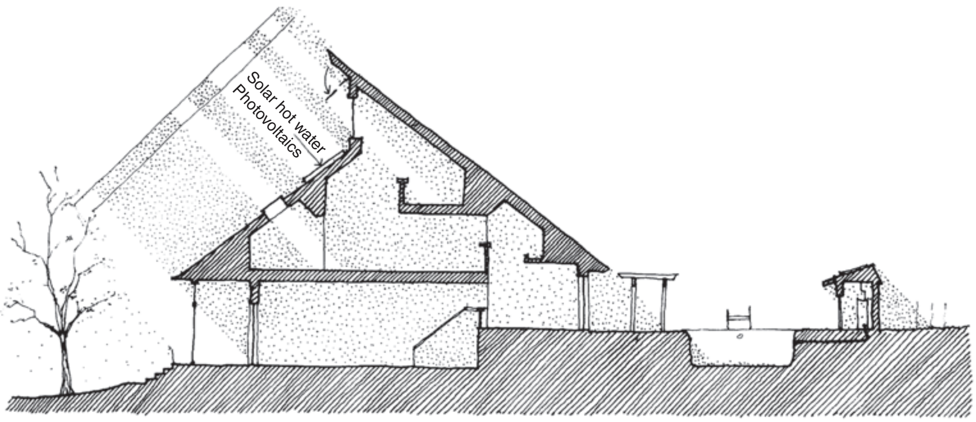


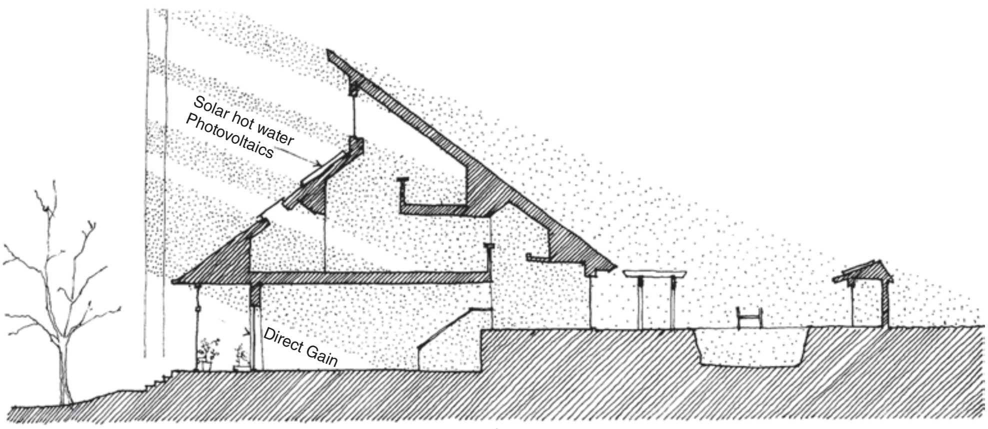
Fig. 3.13 Sun chart for 40°N latitude showing the approximate percentage of clear-day insolation for south-facing windows for each of the 6 maximum hours of sun each month. (From Edward Mazria and David Winitsky. 1976. Solar Guide and Calculator. *Center for Environmental Research, University of Oregon.)*



(*a*)



(*b*)



(*c*)

Interactive Animation

Fig. 3.14 *The band of sun available to a proposed building at solar noon is charted on a north–south section. (a) The summer solstice, where optimum collecting surfaces are at near-horizontal tilt angles. (b) The equinox. (c) The winter solstice, where optimum collecting surfaces are at near-vertical south-facing tilt angles.*

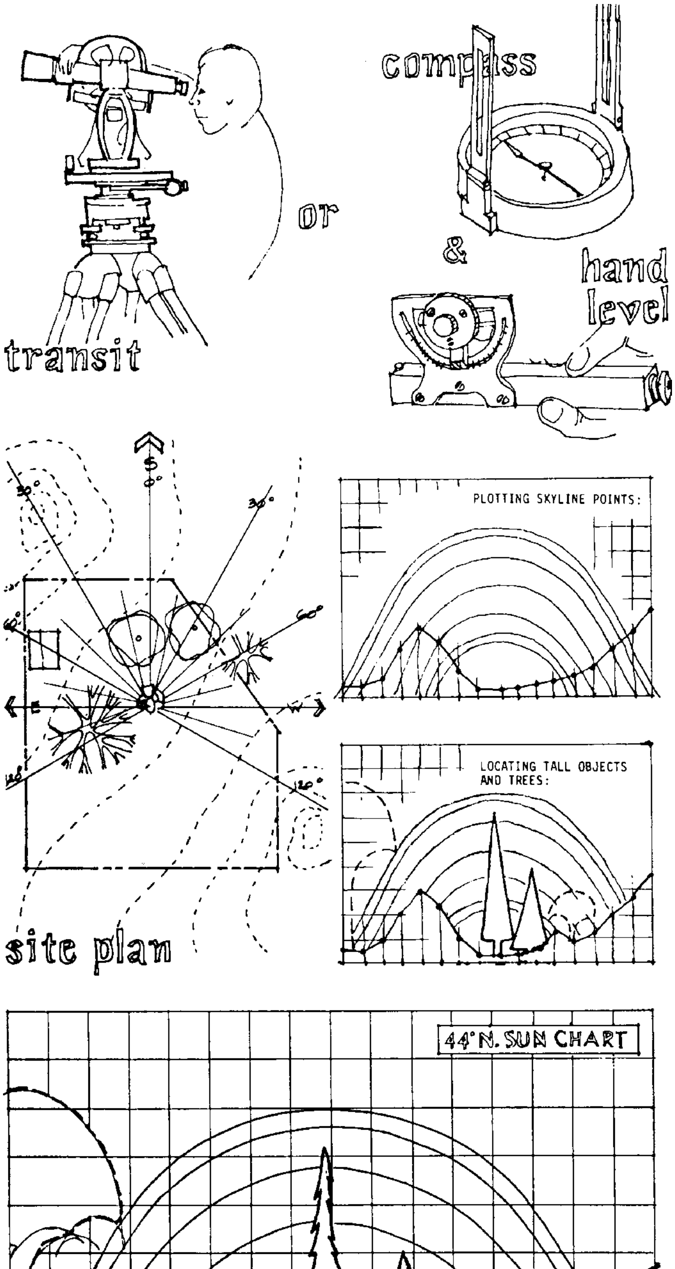


***Fig. 3.15** Charting the skyline from a specific site position. (From Edward Mazria and David Winitsky. 1976.* Solar Guide and Calculator. *Center for Environmental Research, University of Oregon.)*

included on this skyline. If the building form being considered casts shade onto the adjacent site, it can be modified, as necessary, to preserve solar access for the neighbor.

The location evaluated in Fig. 3.15 is a good choice for summer solar usage, such as a swimming pool heater or a solar collector for domestic water heating, which would work well during the six months from March through September; obstructions within this period are few. It is a quite poor location for winter solar collection, however, allowing only about one-fifth of the potential solar gain in the November to January period.

(e) Sun and Shadows: Model Techniques

The graphic site analysis techniques just described have a limitation: Each graph applies only to one particular location on a site. To study multiple locations, multiple graphs must be constructed. By contrast, a three-dimensional model used in conjunction with a sun peg chart (Fig. 3.16) can provide three-dimensional patterns of sun penetration as they change over time, for any position, indoors or out, in/on the model. Models are initially a bit time-consuming to build, but can reduce analysis time when considering alternative locations on a site, alternative window and space combinations, alternative shading devices, and so on. Perhaps most important to a designer, models suggest three-dimensional solutions, because a volume is being tested rather than merely a plan or section. If sun obstructions exist far from a site (such as shading by nearby mountains), it might be better to rely on graphs rather than trying to build a huge model.

A *sunpeg* chart, correctly attached to a model of any scale, allows a designer to quickly determine exact sun penetration and shadow patterns at many times for any date. Sunpeg plots are important tools for a site-conscious designer throughout the design process.

In Fig. 3.16, a model is observed at a sun position corresponding to 3:00 P.M. on December 21. At the afternoon end of the 6-hour period of best solar collection, it can be seen that sun still fills the south-side circulation space and even enters spaces beyond. It can also be seen that passing from these spaces into the circulation space might involve considerable glare because the sun is so low in the sky. In such a case, vertical fins inside the south glazing would help intercept and diffuse direct solar radiation while still permitting solar heat gain.

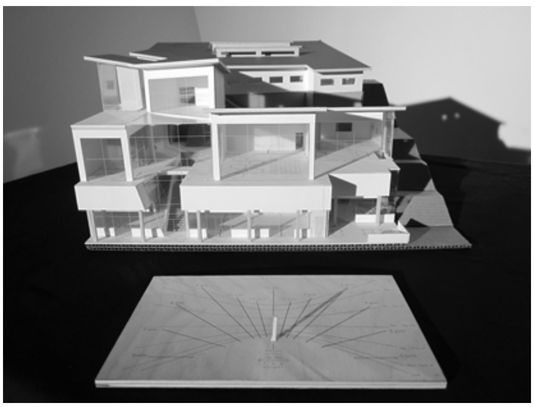


Fig. 3.16 *A model of a small building with a glazed open-frame circulation space on the south side is observed at the sun's position at 3:00 P.M. on December 21 through the use of a sunpeg chart. (Photo by Tyler Mavichien; © 2013 Alison Kwok; all rights reserved.)*

(f) Controlling Solar Reflections

The use of highly reflective (or "mirror") glass to reduce envelope heat gain in office buildings has increased the frequency of annoying solar reflections from buildings (Fig. 3.17). Large areas of nonmirror glazing, such as found on passive solar-heated or glass-box buildings, can also cause reflection problems. Glass and plastic glazing materials become more reflective (less transmissive) as the angle of incidence of solar radiation moves away from a line normal (perpendicular) to the glazing. Thus, the intensity of reflection is greatest (and the transmission of solar gain is least) when the sun's rays are nearly parallel to a surface.

Because the most intense reflections occur when the sun's rays are nearly parallel to a wall, such reflections are fairly easily blocked or intercepted. For example, foliage (Fig. 3.18) can intercept reflected sunlight from a south-facing window without blocking solar collection during the best hours. Another common approach is to

Fig. 3.17 Mirror-glass windows in a newer office building (left) in San Francisco, California, cast strong reflections on the north- and west-facing walls of an older building next door. Although this reflected radiation/heat might occasionally be welcome in winter, the resulting glare can be intense. In summer, the older building is particularly disadvantaged by additional thermal loads on its envelope. (© 2009 Alison Kwok; all rights reserved.)

use external projections around windows, as in Fig. 3.19. Using a model and sunpeg chart is a good way to explore façade reflections. Using mirrored surfaces to represent reflective glass on a model will make resulting reflections evident even when complex geometries are involved. Several high-profile incidents of unacceptable reflections have been reported over the past decade; two in particular involved the Disney Concert Hall (Los Angeles) (Fig. 3.20) and the Vdara Hotel (Las Vegas).

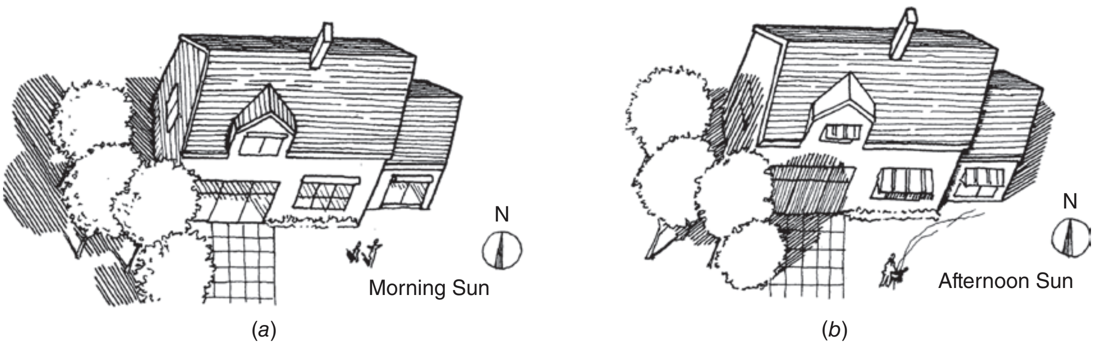


Fig. 3.18 Selective protection from reflections. (a) The trees standing west of this south window wall do not interfere with solar access during the best hours for solar collection (around noon), nor do they prevent early morning sun from entering the windows. Any reflections of the early morning sun are intercepted by the trees before they can annoy those in nearby buildings. (b) The late afternoon sun is blocked by the trees before either solar gain or reflections can occur.

Fig. 3.19 The "eggcrate" shading devices shown on the southeast corner of an office building in Nepal reduce solar heat gains by blocking acute sun angles from either side of the window. (© Ayush Vaidya; used with permission.)

Fig. 3.20 After construction, modifications were made to the highly polished stainless steel exterior of Walt Disney Concert Hall in Los Angeles, California, to reduce reflectance to the neighboring condominiums; surfaces now have a matte finish. (Frank Gehry, 2003; © Karen Tse; used with permission.)

3.7 SOUND AND AIRFLOW

Sound and airflow are discussed together because they are so difficult to separate in a site analysis. Many buildings that could be opened for ventilation or cooling by breezes rely instead on forced ventilation because of noise that would accompany breezes through an open window. Pollution is another potential deterrent to natural ventilation. Almost any object or device that reduces noise will also reduce the velocity of a breeze, as is true of most filtering devices used to remove dust particles.

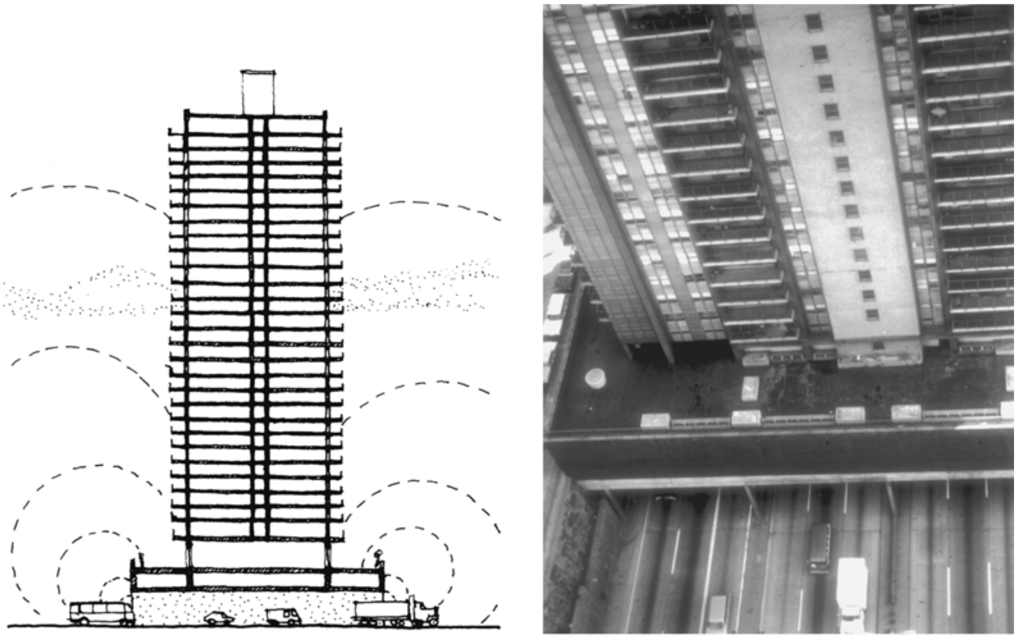
(a) Noise

Any unwanted sound is termed *noise*. The urban building in Fig. 3.21 is unusual both in its potential for wind-driven ventilation—air moves freely below it as well as around it—and in the extraordinary intensity of airborne traffic noise.

Two key characteristics of cities contribute to increased noise at street level. These are hard surfaces that reflect (rather than absorb) sound and parallel walls that intensify sound by interreflection rather than dissipating it. Increasing horizontal and vertical distances from urban noise sources affect outdoor noise levels in various ways, as shown in the graphs of Fig. 3.22. Unfortunately, obtaining much distance between noise source and receiver in dense urban areas is quite difficult.

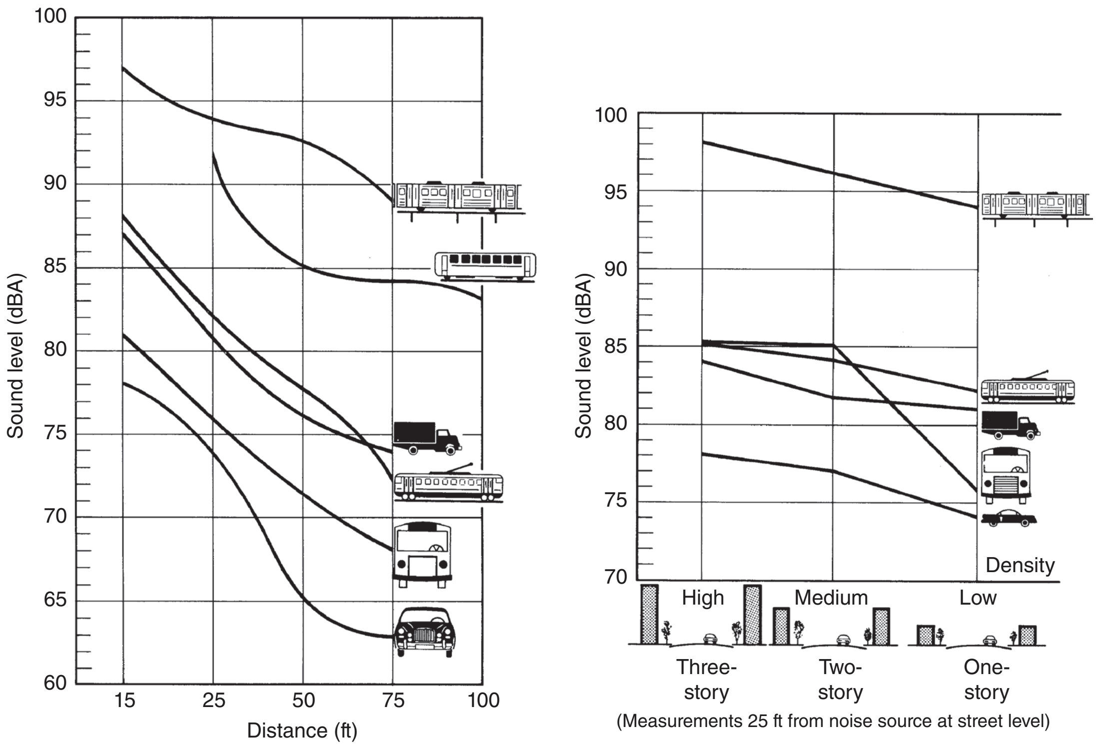
Although building surfaces are generally made of hard materials for durability, softer and multiplaned materials (such as plants) are desirable from an urban noise-reduction viewpoint. Their impact on measured sound levels may be slight, but visually softer surfaces reinforce a perception of acoustically softer environments (much as the sound of running water reinforces our perception of cool environments). Fountains are especially useful sources of *masking sound*; they can be kept flowing as long as a noise persists, and they can enhance the cooling function of natural ventilation via evaporative cooling, especially in drier climates. Not all spaces benefit from masking sound; where a single sound source is expected to predominate over all others, masking sound will interfere and become unwanted "masking noise."

Where site conditions allow, barriers to street noise can be installed that cast *sound shadows* on a site (Fig. 3.23). Such barriers may do little to reduce



(*a*) (*b*)

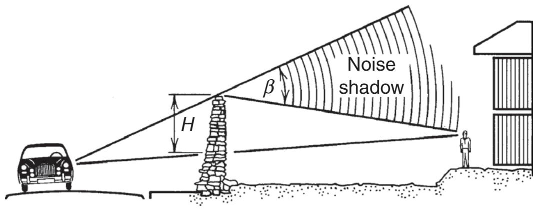
Fig. 3.21 *Apartment buildings in series straddle the approach ramps to New York City's George Washington Bridge. (a) Section along the freeway. (b) Looking down to the freeway. These buildings were the scene of a study linking noise levels with reading disabilities for occupants of the apartments. (From Cohen et al., 1973.)*



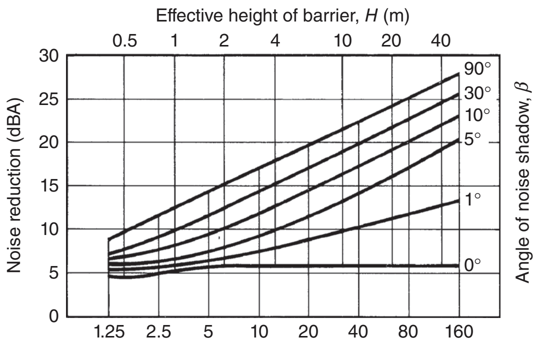
(*a*) (*b*)

Fig. 3.22 *Predicting noise levels outdoors. (a) Distance as a factor influencing sound pressure level. (b) Building height as a factor in noise propagation. (From Clifford R. Bragdon. 1971.* Noise Pollution: The Unquiet Crisis*. University of Pennsylvania Press. Reprinted by permission.)*

(a)



(b)



(c)

Fig. 3.23 *Outdoor noise barriers. (a) A noise barrier abutting a highway in central Oregon. (Photo by Nathan Majeski.) (b) To determine the approximate noise reduction (in decibels) due to an outdoor barrier, construct a section locating the noise source (N), the solid barrier (B), and the receiver's location (R). On this section, determine the effective height (H) of the barrier and the diffraction angle (β) with the resulting "noise shadow." Enter graph (c) with H and β; where the lines intersect determines the noise reduction in dBA (left axis). A reduction of 10 dBA is perceived as half as loud as the original source. Note the perceptible noise reduction from simply breaking the line of sight (β = 1°). (From Doelle, 1972. Reprinted by permission.)*

TABLE 3.3 Air Pollution: Sources and Effects

Gas or Pollutant	Sources	Effects
Carbon monoxide (CO)	Gasoline-powered vehicles, industry using oil and gas, building heating using oil and gas, biomass combustion	Enters human bloodstream rapidly, causing nervous system dysfunction and death at high concentrations; interferes with self-cleansing of atmosphere
Carbon dioxide (CO_2)	Fossil-fuel combustion, deforestation	Contributes to greenhouse effect
Methane (CH_4)	Rice fields, cattle, landfills, fossil-fuel production	Contributes to greenhouse effect
Sulfur oxides such as sulfur dioxide (SO_2) and sulfur trioxide	Industry using coal and oil; heating using coal and oil; power plants using coal, oil, and gas; ore smelting	Acid rain, damaging plants and attacking building skin materials; irritates human respiratory tract and complicates cardiovascular disease; decreases visibility in atmosphere
Nitrogen oxides (NO_X) such as nitric oxide (NO) and nitrogen dioxide (NO_2)	Gasoline-powered vehicles, building heating using oil and gas, industry and power plants, biomass burning	Acid rain, damaging plants and attacking building skin materials; irritates human eyes, nose, and upper respiratory tract; triggers development of smog; decreases visibility in atmosphere
Nitrous oxide (N_2O)	Nitrogenous fertilizers, deforestation, biomass burning	Contributes to greenhouse effect
Hydrocarbons (compounds of hydrogen and carbon)	Petroleum-powered vehicles, petroleum refineries, general burning	Promotes smog; toxic to human beings at high concentrations
Chlorofluorocarbons	Aerosol sprays, refrigerants, foams	Contributes to greenhouse effect and to stratospheric ozone depletion
Particulates (liquid or solid particles smaller than 500 micrometers)	Vehicle exhausts, industry, building heating, general burning, spore- and pollen-bearing vegetation	Promotes precipitation formation; some are toxic to human beings; some pollens and spores cause allergic reactions in human beings

Sources: Adapted from Marsh (1991) and Graedel and Crutzen (1989).

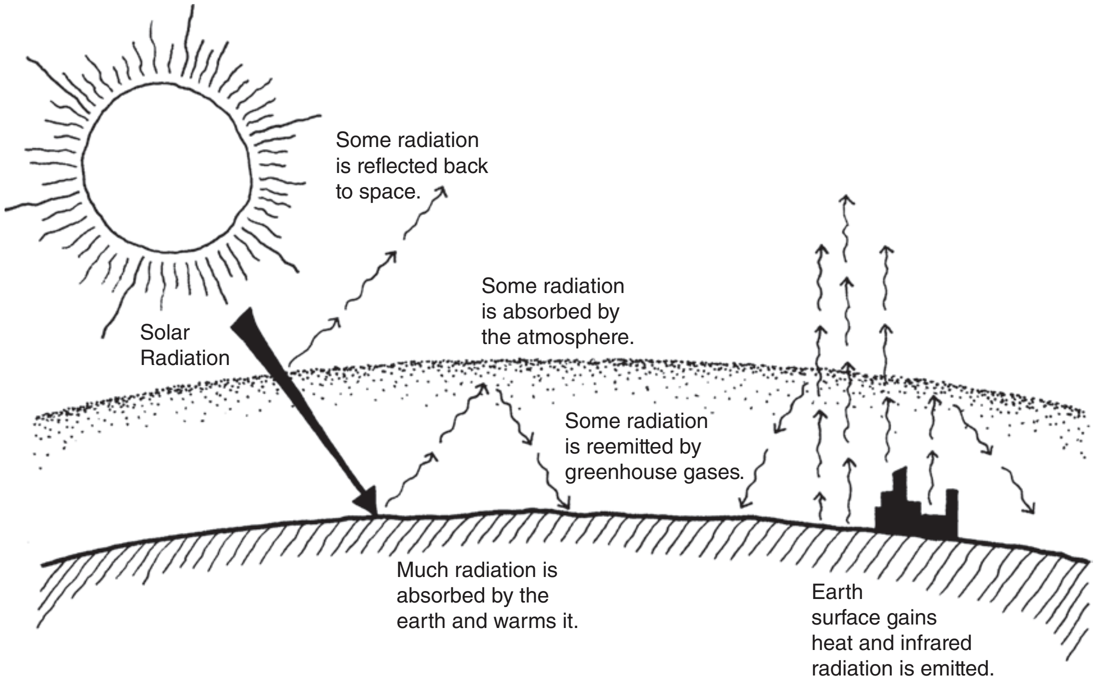
noise reaching upper windows, but activities near the ground can be given much lower noise levels, especially near the barrier. Many cities now require such barriers between new housing developments and highways or railroads.

Building mechanical equipment is another urban noise source. Many noise complaints involving buildings are caused by air-conditioning equipment. When densely packed buildings are forced to rely upon mechanical cooling, such closeness makes the noise produced by the systems difficult to avoid. Noise is generated both by the air-conditioning compressor and by the large quantities of outdoor air that must be moved through outdoor condenser units. Attempts to surround condensing equipment with noise shields can hinder its operation, since a noise barrier is usually a barrier to airflow. Fortunately, energy-efficient equipment tends to be quieter, although not silent.

In residential neighborhoods, the greater distance between buildings might be expected to lessen mechanical equipment noise problems. Yet the much lower ambient (or background) sound level in residential areas is one of their more appealing characteristics, and an intruding compressor on a hot summer night can irritate neighbors who would like to enjoy cool—and quiet—night breezes.

(b) Air Pollution

Problems of global importance are resulting from air pollution; these are summarized in Table 3.3. Building construction and operation contribute to air pollution. An enhanced *greenhouse effect* (Fig. 3.24) fueled by human emissions of a variety of gases threatens to bring about substantial global climate change. A vast majority of international scientists now firmly believes such change is



Interactive Animation

Fig. 3.24 *The greenhouse effect traps heat in the Earth's upper atmosphere. Clouds and particles in the atmosphere reflect about one-fourth of incoming solar radiation while blocking about two-thirds of the heat that the Earth would otherwise lose to outer space. Historically, the atmosphere kept the Earth about 33°C (60°F) warmer than it would be without this heat-trapping process. Increases in greenhouse gas concentrations will reflect more incoming solar radiation but block even more outgoing radiation, resulting in global warming and regional changes in climate. (Drawing by Amanda Clegg.)*

actively under way. The greenhouse effect is being amplified because gases that block the outgoing flow of long-wave radiation (heat) from the Earth's surface are accumulating in the atmosphere. Energy production and use (especially of fossil fuels) are contributing heavily to these greenhouse gas emissions, which include carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs). Another ongoing threat from pollution is stratospheric ozone depletion, with potentially devastating consequences to ecosystems due to increased ultraviolet radiation received at the Earth's surface.

Building designers can influence these negative trends in several ways. First, by designing for greater energy conservation and by utilizing renewable energy sources for building systems, they can help to greatly reduce the air pollution caused by electric power plants and by burning fuels on site. Chapters 8, 9, 10, and 11 are concerned largely with this approach. Second, designers can specify materials and equipment that, through their manufacture or operation, lessen air pollution. This suggests avoiding fuel combustion (coal, oil, trash, wood, and natural gas, roughly in descending order of air pollution threat). This philosophy also encourages selection of refrigeration equipment that uses environmentally friendly refrigerants, as well as insulation and upholstery products made using CFC-free processes. Many of these practices are mandated by codes, but a designer can always go further and seek out the most environmentally benign products.

Buildings are substantial contributors to air pollution: the fuel combustion within, the power plants that supply electricity, the incinerators and landfills that receive waste from buildings. Buildings and power plants are major contributors to expansion of the greenhouse effect and are the primary causes of acid rain (sulfur oxides) and smog (nitrogen oxides). The transportation systems that take people to and from buildings are another major air pollution source. We purposefully design buildings to utilize "fresh" air, whether by natural or forced ventilation; we must logically then also design buildings to preserve our fresh air resources

Fig. 3.25 *Reactive protection of an outdoor air intake. A loading dock near an intake was a source of indoor air pollution from truck motor fumes, prompting the installation of a warning sign.*

(see Fig. 1.1). The less nonrenewable energy buildings consume, the cleaner the outdoor air will be.

On site, local sources of air pollution must be minimized and, as far as possible, isolated. Combustion gases pose a threat, especially where vehicles engage buildings (Fig. 3.25). Idling truck motors at loading docks or automobile motors at drive-up service windows can threaten building occupants through openings such as doors and windows; mechanical system fresh air intakes are particularly vulnerable, because outdoor air is intentionally drawn into them. Again, consider the neighboring buildings: Will the thoughtless location of some activity on your site threaten a neighbor's fresh air?

(c) Wind Control

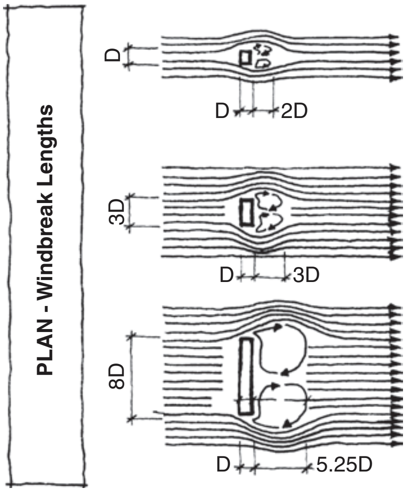
For most buildings, wind (like sun) changes from resource to detriment with the change of seasons. In many locations, wind also changes its prevailing direction with the seasons. Control of wind often means developing winter-wind-sheltered areas while designing to increase summer wind speeds. From spring through fall, outdoor spaces might benefit from a difficult-to-accomplish transition from site-as-"barrier" to site-as-"connector" on a daily basis—resulting in less wind during cool morning hours, more during hot afternoon hours. Fortunately, winds are generally weakest in the early morning and strongest in the afternoon because of the effect of the sun's heating on the surrounding environment.

Generalized patterns of wind flow around thin windbreaks and thicker buildings (Fig. 3.26) can help a designer understand where reduced and increased airflows may occur. These patterns, however, are much more complicated than they first appear and are highly influenced by objects upstream, to the sides, and downstream of the wind-directing object being analyzed. Wind-tunnel tests using scale models are far more reliable design tools than these generalized patterns. Unfortunately, such tests are expensive and still fraught with opportunities for misprediction. These considerations notwithstanding, a site can and should be analyzed as accurately as possible for site-specific seasonal wind patterns. Readily accessible software should soon make this effort less challenging (Fig. 3.27).

Before it reaches an obstacle, wind slows, builds up a positive pressure, and turns upward or sideways. As it passes the obstacle, it increases speed, and a reduced pressure occurs at the sides of and behind the obstacle. Such pressure differences, flow patterns, and the size and shape of the wind-protected areas behind an obstacle can be used to beneficially control air motion, both inside and outside of a building. Wind will ultimately return to its original flow pattern after encountering an obstacle such as a windbreak or a building.

Windbreaks are commonly used to protect outdoor areas; these can be fences or plants. Figure 3.28 shows the relative reduction in wind velocity at the level of a windbreak as wind approaches and then passes. The distances (horizontal axis) are in units of the height of the windbreak. Note that the densest windbreak produces the greatest reduction in wind speed behind it—but that the wind recovers its full velocity closer to such a barrier, compared to a less-dense windbreak. Thus, the more dense the windbreak, the greater the reduction in wind speed but the smaller the area so affected.

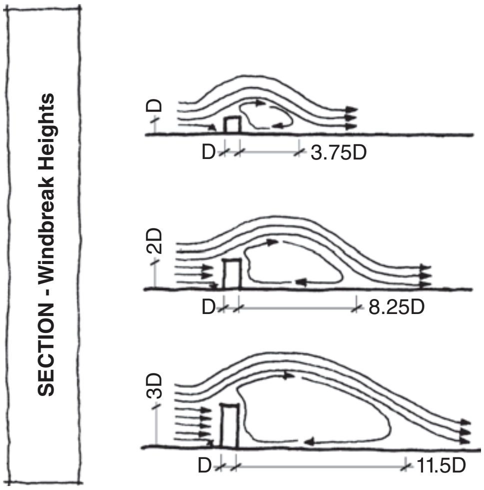
Increased wind speed can be produced by a gap in a windbreak. Figure 3.29 shows this effect. Although a gap is a threat to protection from unwanted winter winds, it is an opportunity for enhancement of desirable summer winds. Given constant prevailing summer wind directions, a windbreak gap could provide a small area of a site with above-average air motion. The Strata SE1 in Fig. 3.30 is a 43-story skyscraper, which houses 408 apartments. The building features three wind turbines rated at 19kW each that are designed to



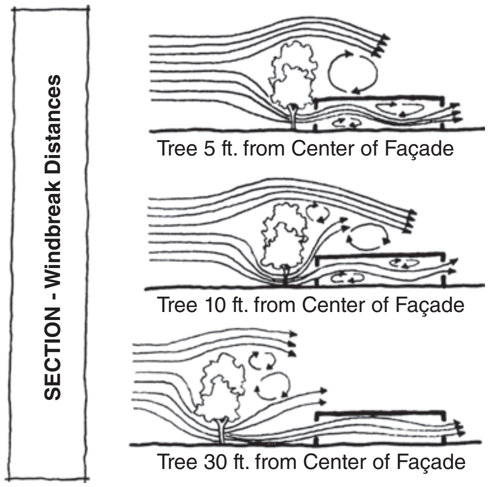
(a)

Wind Speed Reduction (%)				
Density of Belt	Average Over First: **50 Yd**	**100 Yd**	**150 Yd**	**300 Yd**
Very Open	18	24	25	18
Open	54	46	37	20
Medium	60	56	48	28
Dense	66	55	44	25
Very Dense	66	48	37	20

(b)



(c)



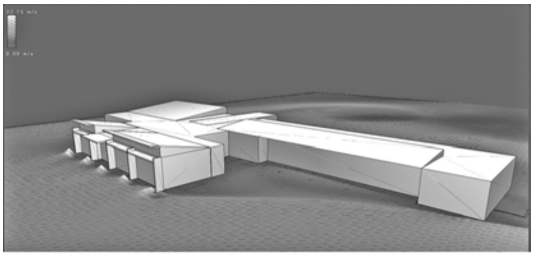
(d)

Fig. 3.26 *Approximate patterns of wind around objects. (a) Effects of different barrier lengths (widths). (b) Reduction in wind speed due to windbreak density. (c) Effects of different barrier heights. (d) Wind flow through trees and buildings. (Reproduced with the permission of the American Institute of Architects; © 1981, AIA. Redrawn by Jonathan Meendering.)*

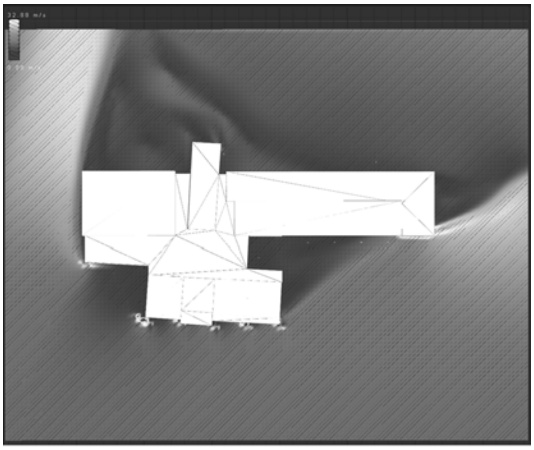
produce 50MWh of electricity per year. A recent visitor to the building found that vibration of the wind turbines disturbed occupants.

Wind flow around buildings is a complex matter; nevertheless, some general patterns for shelter areas are shown in Fig. 3.26. Figures 3.31 and 3.32, on the other hand, show wind behavior to be expected from typical building arrangements. Some patterns seen in the situations shown in Fig. 3.32 include:

- With the bar effect (*a*), the downward-spinning wind behind a building can reach 1.4 times the ambient wind speed.



(*a*)



(*b*)

Fig. 3.27 *Visualization of wind patterns around a simple, 3D building model (a), can also be viewed in plan (b), using Autodesk Vasari. (Autodesk screen shots reprinted with the permission of Autodesk, Inc.)*

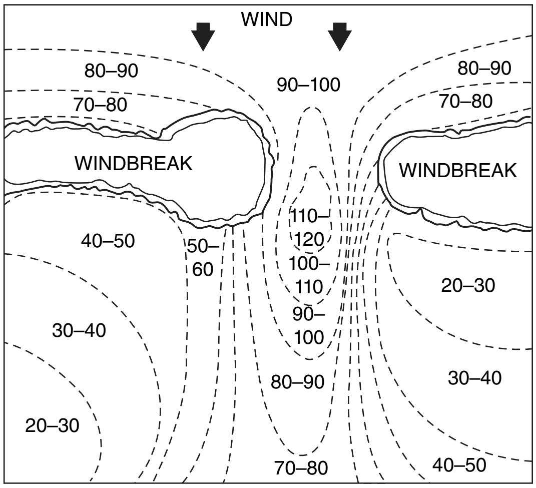


Fig. 3.29 *Wind speeds accelerate through a gap in a windbreak. Numbers indicate the percentage of the incoming (unaffected) wind speed. (From Caborn, J. M. 1957.* Shelterbelts and Microclimate. *Edinburgh: H.M. Stationery Office. Cited in McPherson, 1984.)*

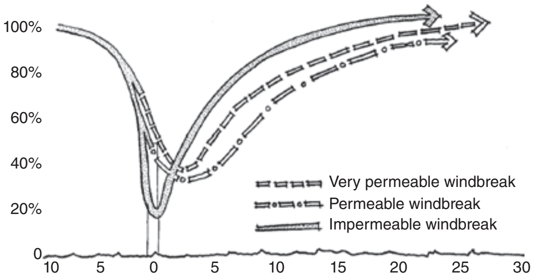


Fig. 3.28 *Wind speed reduction behind windbreaks of varying permeability. Solid (impermeable) barriers produce the lowest wind speeds, but these are effective for the shortest distance beyond the windbreak. Units of distance = heights of windbreak. (Brown and Gillespie, 1995. Redrawn by Erik Winter.)*

Fig. 3.30 *Strata SE1, London (BFLS, 2010) is anticipated to produce 8% of its total estimated energy consumption. (©Tisha Egashira; used with permission.)*

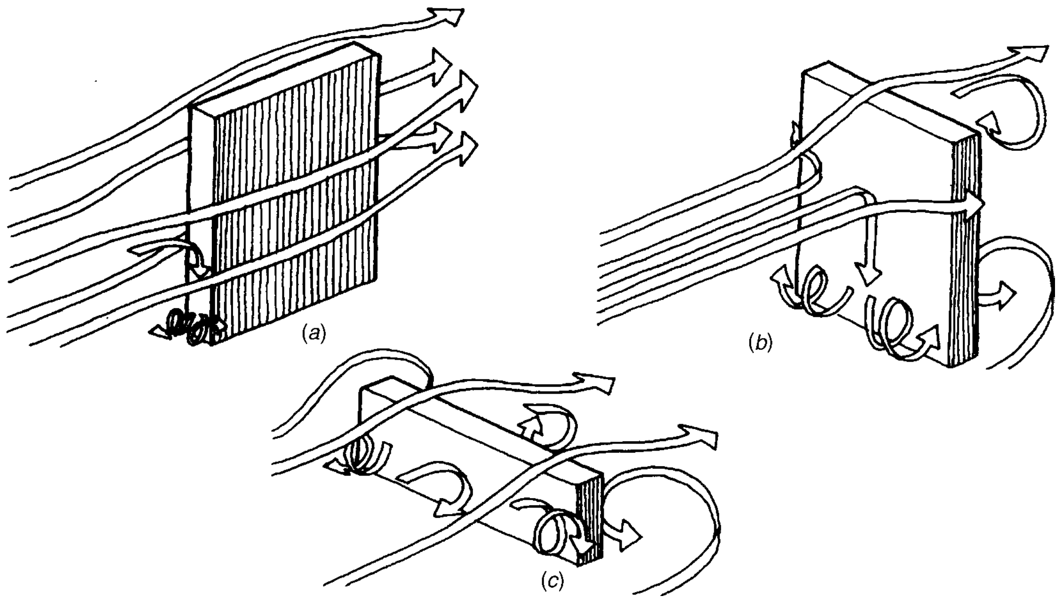


Fig. 3.31 *Wind patterns around single buildings. (a) Tall, slender buildings: height greater than 2.5 times the width. (b) Tall, rather wide buildings; height between 2.5 and 0.6 times the width. (c) Long buildings; height less than 0.6 times the width. (From Beranek, W. J. "General Rules of the Determination of Wind Environment," in* Wind Engineering, *J. E. Cermak [ed.], Vol. 1; © 1980, Pergamon Press Ltd. Reprinted by permission.)*

- With the Venturi effect (*b*) and few obstructions upwind or downwind from the narrow neck of a building, wind through the neck can reach 1.3 times the ambient speed, up to heights of 100 ft (30 m), and 1.6 times the ambient speed at about 165 ft (50 m) in height.
- The gap effect (*c*) begins to occur with perpendicular winds and buildings of more than 5 stories (50 ft [15 m]) in height; by 7 stories, wind speeds 1.2 times the ambient can occur through the gaps; by 60 stories, gap wind speeds can be 1.5 times the ambient.
- For higher buildings (*d*), increased wind speeds occur at the corners (localized within a radius from the corner equal to the width, d, of the building); where height is 50 ft (15 m), wind speed can reach 1.2 times the ambient; for heights above 115 ft (35 m), wind speed can be 1.5 times the ambient. Where two towers approach each other, increased wind around corners and between the towers can go as high as 2.2 times the ambient for towers 330 ft (100 m) high.
- Increased wind speed and turbulence within the wake of buildings (*e*) can be especially serious for towers at heights from 16 to 30 stories, where wind speeds can reach 1.4 to 2.2 times the ambient.

Beranek (1980) discussed methods for charting the shelter areas in such building groups. Localized effects of wind turbulence between buildings can have a particularly powerful impact on entryways. People leaving the calm of a building lobby are often unprepared for the speed and turbulence of channeled winds just beyond the doorway.

Wind flow for the cooling of buildings is discussed in detail in Chapter 10.

(d) Ventilation and Cooling

Outdoor air is purposefully brought into buildings for two distinct reasons. *Ventilation* (technically speaking) is the delivery of fresh air to building interiors to replenish the oxygen used by people and to help carry away a variety of indoor pollutants. Ventilation is desirable year-round and is associated with the provision of acceptable indoor air quality. Recommended minimum rates of ventilation airflow are found in Appendix F. *Passive cooling* (informally termed ventilation) replaces heated

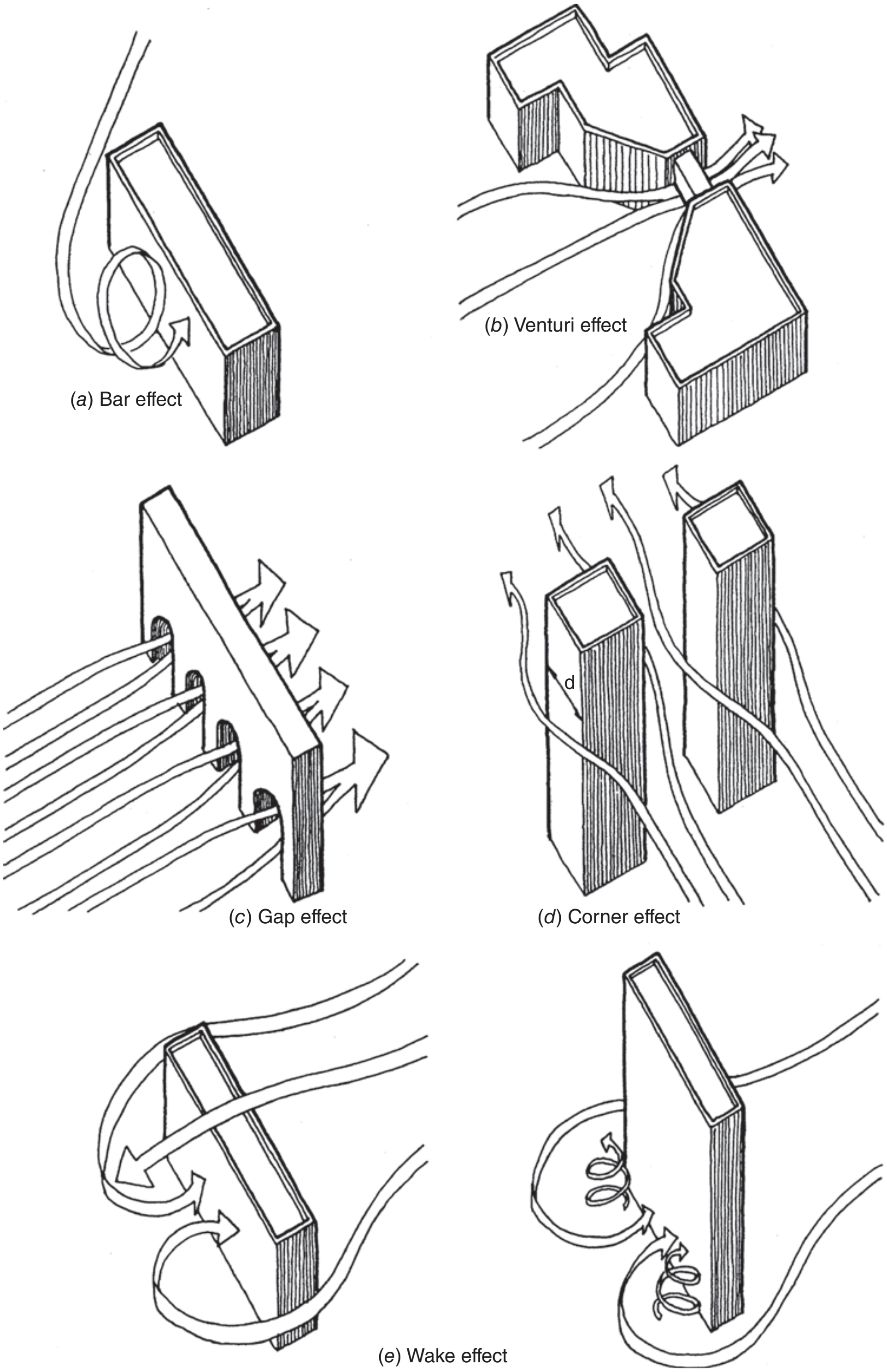
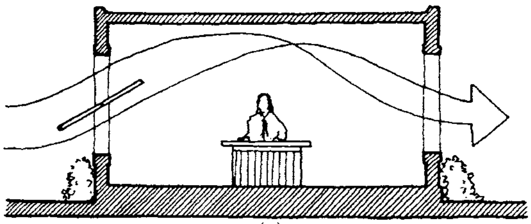


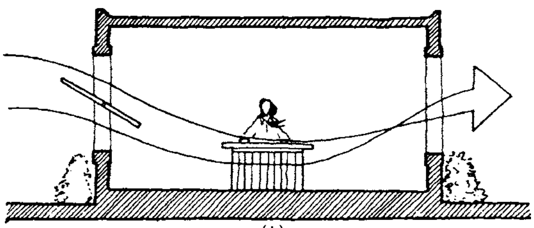
Fig. 3.32 *Wind patterns among building clusters (see text for quantification). From Gandemer, J. "Wind Environments Around Buildings: Aerodynamic Concepts," in* Wind Effects on Buildings and Structures*, K. J. Eaton (ed.); © 1977, Cambridge University Press. Reprinted by permission.*

indoor air with cooler outdoor air. Passive cooling by cross ventilation or stack ventilation is a seasonal opportunity (and in many climates a seasonal need as well), limited to times when the outdoor air temperature is lower than the indoor air temperature, and the outdoor humidity is at or below that desired indoors. When outdoor air temperatures are about the same as interior temperatures, breezes might still be useful to increase interior air motion, thus extending the comfort zone, as discussed in Chapter 4.

Although airflows for indoor air quality control and for cooling are both commonly (and confusingly) referred to as "ventilation," they are not identical design responses. Building codes/standards typically rigidly define ventilation requirements for air quality. This is not the case for ventilation for cooling. Airflows for effective passive cooling can far exceed airflow rates for control of air quality. The influence of cooling ventilation requirements on building siting and window size and placement is considerable. Figure 3.33 illustrates the differing approaches to these two uses for airflow and suggests that window position and human occupants be considered together in design.



(*a*)

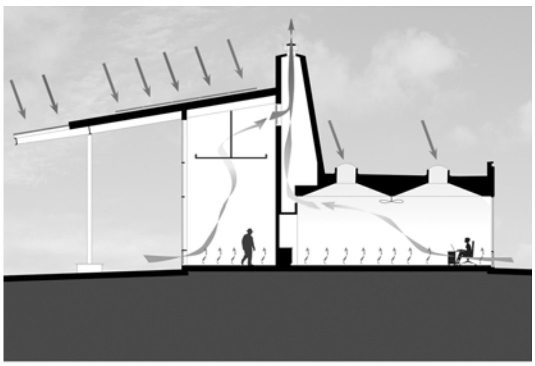


(*b*)

Fig. 3.33 *Ventilation with and without occupant cooling. The size and position of a window will influence the flow of air within a space. (a) Ventilation: the window directs breezes upward, removing hot air at the ceiling. Airflow has minimum contact with occupants. (b) Space ventilation and people cooling: the window directs breezes toward the floor and across occupants and provides a direct people-cooling effect from air motion and fresh air for the space.*

Two interesting buildings designed to use the wind appear in Figs. 3.34 and 3.35. Portland Community College in Newberg, Oregon, is a 13,500 ft^2 (1254 m^2) facility designed as the

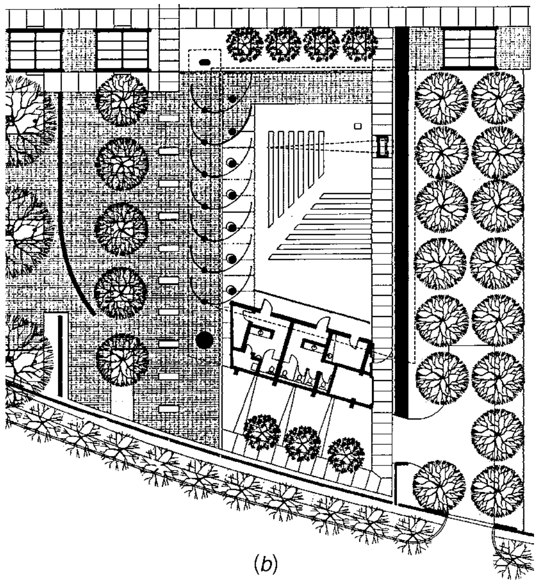
(*a*)



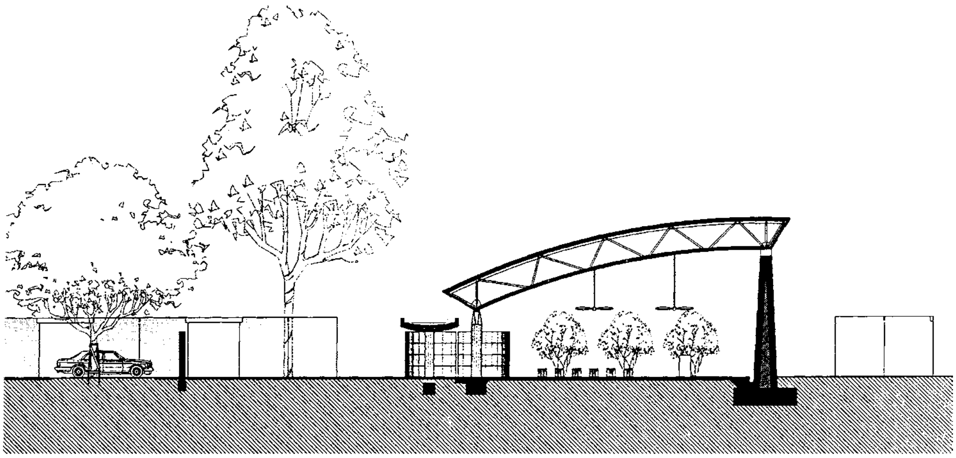
(*b*)

Fig. 3.34 *(a) Natural ventilation and passive cooling strategies articulated by the ventilation stacks at the Portland Community College Newberg Center in Oregon; (b) Small ventilation turbines in each stack help to draw fresh air through the louvers along the building's perimeter and exhaust through the top of the stack. (Photo © Nic Lehoux; used with permission; drawings © Hennebery Eddy Architects; used with permission.)*

(*a*)



(*b*)



(*c*)

Fig. 3.35 *The Beth Israel Chapel and Memorial Garden, Houston, Texas. (a) View from the west. The oversized gutter delivers rainwater to a pond that reflects daylight. Trees on islands in the pond provide evening shade. (b) Plan. Curved walls visually separate the open south courtyard from the roofed chapel, but allow breezes to pass. A narrow triangular roof opening allows a shaft of direct sunlight to fall along the interior north wall, marking the passing of time. (c) Section, south to north. The curved roof sheds rainwater to an oversized gutter above the curved walls. Suspended ceiling fans can augment air motion. (Photo by Timothy Hursley. Courtesy of Solomon Inc., Architecture and Urban Design, San Francisco.)*

first net-zero-energy higher education building in Oregon (and the second in the United States). The second is a chapel in a cemetery in hot, humid Houston, Texas. The architects intended that this shaded, open-air space act as a respite from the sealed, air-conditioned buildings and cars prevalent in Houston. In this building, a funeral becomes a time and place for a reunion with physical phenomena; breezes and shade trees provide cooling, rainwater collected in a pool reflects skylight, and a narrow shaft of direct sun marks its daily path along the rough stone interior north wall.

A building that relies on prevailing winds for cooling must be sited with attention to wind direction. Relatively unobstructed access to breezes is an important design consideration. As seen

TABLE 3.4 Beaufort Scale (Lower Speeds Only)

Beaufort Number	Speed 6 m (19.7 ft) Above Ground			Description of Effects Outdoors	
	m/s	fpm	mph	On Land	Over Water
0	0.3	<88	<1	Smoke rises; no perceptible movement	Smooth sea
1	0.3–1.5	88–264	1–3	Smoke drift shows wind direction; tree leaves barely move	Scale-like ripples
2	1.6–3.4	352–616	4–7	Wind felt on face; leaves rustle	Small wavelets
3	3.5–5.4	704–1056	8–12	Leaves, twigs in constant motion; hair is disturbed; wind extends light flag	Large wavelets; occasional white foam crests
4	5.5–7.9	1144–1496	13–17	Small branches move; dust rises; hair disarranged	Small waves become longer

Source: https://en.wikipedia.org/wiki/Beaufort_scale; accessed July 2013

previously, obstacles upstream from intake openings or downstream near an outlet can substantially reduce the speed—and thereby the cooling effect—of the wind. Wind can cool people in hot weather (primarily by increasing evaporation from the skin), yet it can become an irritant at higher speeds (Tables 3.4 and 4.4). Manual controls for openings are a necessary part of a natural ventilation system. Finally, properly sized and placed openings, with an unobstructed path for airflow through the building, must be provided.

(e) Wind, Daylight, and Sun

The design constraints of both daylighting and wind-driven (cross) ventilation tend to limit building width. Large, multistory hotels are an example; they often fill an entire block, are arranged around a central atrium, and have a floor plan that is only two hotel rooms and one corridor deep. Multistory office buildings used to have a similar form, but increasing urban density and reliance on electric lighting and mechanical cooling have changed design responses considerably (Fig. 3.36). A trend back to arranging office workspaces close to daylight openings is occurring in response to green design concerns; in appropriate climates, buildings are also trending (although slowly) toward including operable windows for fresh air.

When wind and sun are both design considerations, they tend to be influential in opposite seasons. Fresh air, however, is necessary year-round, so even in winter a supply of tempered fresh air is desirable. Figure 3.37 captures some issues surrounding a design decision regarding a clerestory—whether it should face to the north or to the south for a given prevailing wind pattern.

3.8 RAIN AND GROUNDWATER

Most buildings interact with four forms of water: Rainwater and groundwater involve exterior interactions minimally impacted by building codes, whereas potable water and wastewater involve interior services tightly controlled by codes.

Rain, like solar energy, is a generally diffuse, intermittent, and often seasonal resource. It may be collected on site and used as a source of water for building services where other water resources are scarce or of poor quality. Rain, like sun, has an influence on building design: Heavy rains and pitched roofs have long been found in the same locales. Overhangs may extend farther beyond walls exposed to storm winds; gutter and downspout details can become a design feature, as shown in the chapel in Fig. 3.35 and in several other examples throughout the book. A design solution that

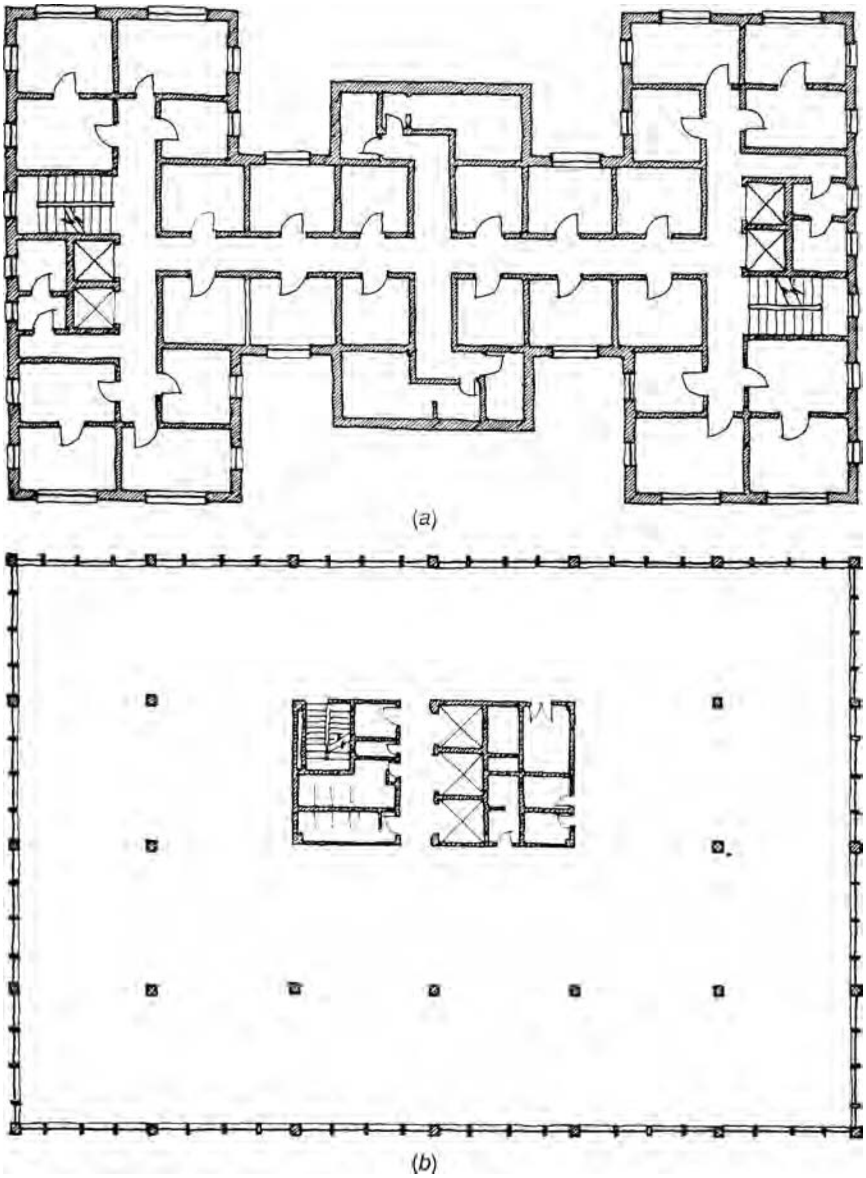


Fig. 3.36 *In contrast to office building plan (a), which provides daylight and natural ventilation in each office, office building plan (b) receives mechanically cooled and filtered air, is less subject to exterior noise, typically provides constant light and temperature throughout, and provides for more rentable floor space on its site. Plan b also allows less daylight to reach the street level, consumes much more electricity (though probably less heating fuel), and thus contributes more waste heat (and possibly noise from mechanical equipment) to its surroundings year-round.*

reflects the combined influences of daylight, wind, and rain is shown in Fig. 3.38.

Once on the surface of a site, rainwater will flow downhill in a sheetlike path, and structures that obstruct this path must make provisions to accommodate the flow. Shallow ditches called *swales* are frequently used to direct rainwater flow. The orientation of a building relative to the slope of a site can also affect surface water diversion, as shown in Fig. 3.39.

Surface water can be used to advantage in thermal, acoustic, and daylighting roles. Hot, dry

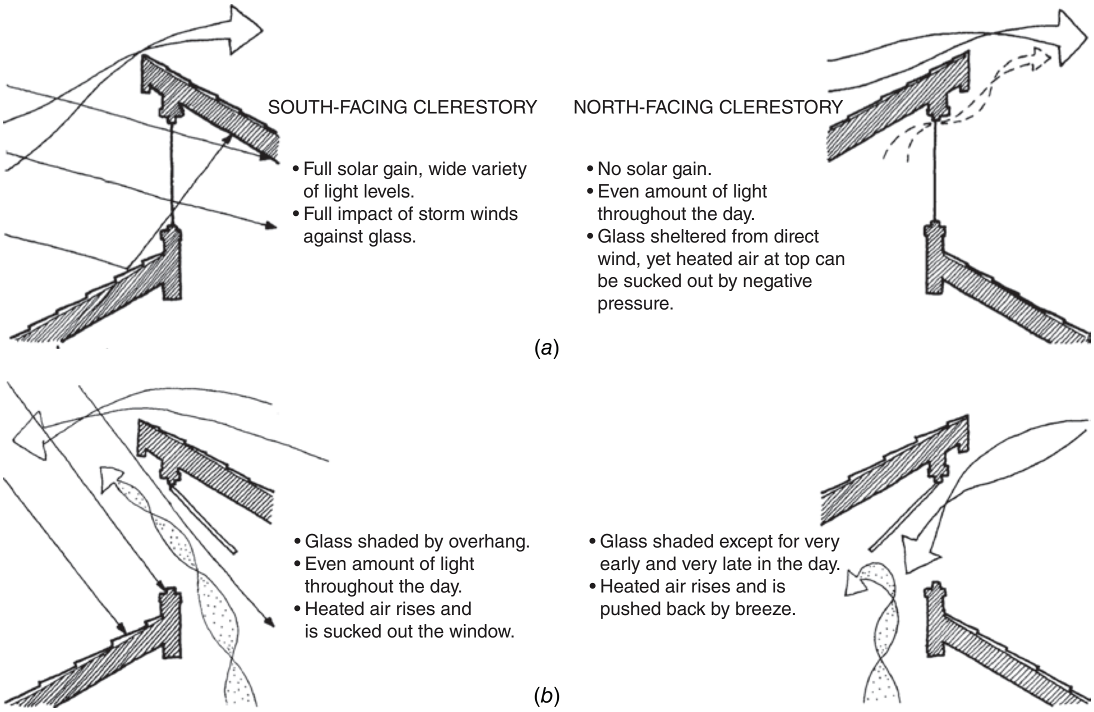


Fig. 3.37 *Some relative advantages of north versus south orientation for a clerestory window/shed roof combination. (a) Winter, with low sun and southerly storm winds. (b) Summer, with high sun and northerly breezes. (These wind directions are prevalent in the Pacific Northwest.)*

Fig. 3.38 *Integrated design is expressed by this gutter detail in the 2005 Cornell Solar Decathlon House. (© Nicholas Rajkovich; used with permission.)*

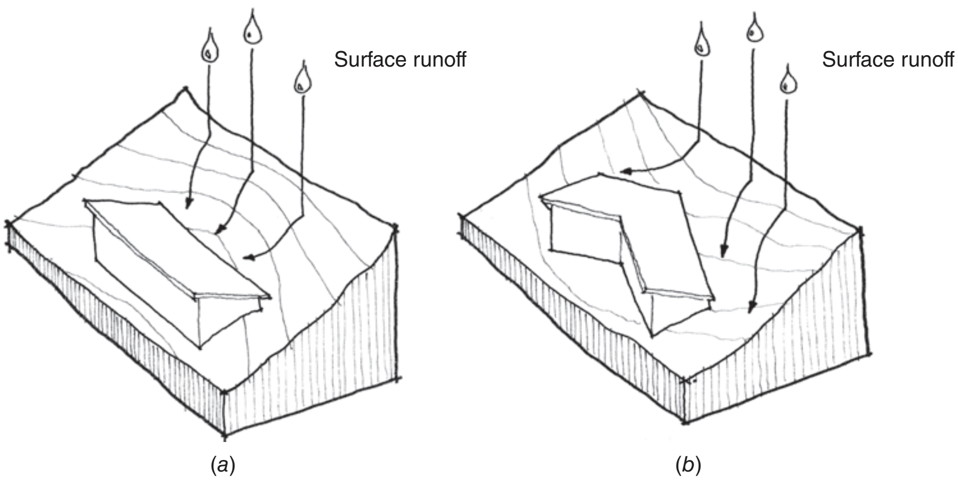


Fig. 3.39 *Rain as surface flow. (a) Where buildings intercept surface water, provisions for diversion are necessary. A building sited as in (b) needs less elaborate provisions, as the form itself is a diverter. (Drawing by Dain Carlson.)*

breezes that pass over water surfaces (and especially through misty sprays above ponds) gain substantial moisture while undergoing a drop in dry-bulb temperature, as a result of the evaporative cooling process. Such conditioned air can provide improved comfort in hot, dry conditions. If a water feature also provides the sound of running water, it can serve to mask noises such as traffic or conversations in adjacent rooms.

Surface water plays a more complex role in daylighting due to the reflection characteristics of water. The surface of water is highly reflective to light striking at low angles of incidence; for example, the reflections of the setting sun from the small pond will illuminate the ceiling and east wall of the chapel shown in Fig. 3.35. On the coast, reflected sunlight from an infinitely huge ocean or lake surface can throw a blinding sheet of light toward buildings on the shore. Conversely, sunlight near noon in summer strikes a water body at high angles of incidence—nearly perpendicular at southern U.S. latitudes. Water is highly absorptive and transmissive to radiation at these angles, thereby reflecting relatively little light. Therefore, water bodies east, south, and west of buildings can provide increased reflected light on sunny winter days and somewhat decreased reflected light in summer, relative to alternative surface materials. On heavily overcast days, however, when the sky is uniformly gray (and the least amount, but most glare-free quality, of daylight is available), water surfaces will not be particularly helpful in directing daylight.

The reflection of sunlight off moving water tends to be in sparkling patches of always-changing patterns. This can act as a fascinating design feature, or it can be annoying (perceived either as a welcome distraction or as glare). Reflected off a matte-finish ceiling, such dancing light might be welcome; reflected directly into someone's eyes or onto a work surface, it easily becomes a problem. What one viewer sees as sparkle may be seen as glare by another.

Groundwater is generally avoided by designers whenever possible, as it is a threat to foundations and belowground spaces. This concern must be an integral part of site planning. In urban areas, dryer soil conditions are often the norm as ponds are drained, streams are contained, and hard surfaces impede percolation of water into the soil.

Groundwater has interesting thermal potential as a heat sink, providing a place to discharge building heat in summer and providing heat for winter building heating. The quantity of groundwater available to act as a heat sink varies with geographic location and subsurface conditions, and little macroscale information is available to indicate its potential on a given site. Ground-source heat pump systems using soil and/or groundwater as a heat sink/source are becoming common.

As with any site resource, ambient groundwater and soil temperatures can be changed through use over time, but by how many degrees and how quickly is difficult to predict. Groundwater pollution is another risk, through increased handling of groundwater or from refrigerants in the heat pump equipment. As a result of such concerns, many localities now strictly regulate the use of groundwater as a heat sink/source. In some locales, geothermal—referring to high-temperature water or steam—resources may be tapped for building use. *Geothermal* is a distinctly different concept than *ground source*.

The ready ability of water to conduct and store heat, which leads to its common use as a heat sink and heat-transfer medium, also makes it a thermal nemesis when heat containment is the design objective. Heat containment is a serious concern for hot water tanks and rock bins in solar-heated buildings (as well as underground wall and floor surfaces in heating-dominated climates). There is little point in storing heat from solar collectors in an underground tank if surrounding groundwater is allowed to strip the tank of its heat.

Snow has special site design implications: It stores water for delayed runoff, provides a blanket of thermal insulation, absorbs sound, and reflects more solar radiation than almost any other naturally occurring surface. Wind patterns can deposit snow much more thickly in some places on site than in others, for better or worse. Snow hampers the movement of external control devices such as awnings or thermal shutters, can collect to excess on external light shelves, and can create disabling glare if it reflects low winter sun into view windows.

3.9 PLANTS

Plants on a building site can play several roles. They affect the absorptivity and emissivity of the Earth's surface relative to solar radiation; they are part of both the food and water cycles (affecting surface permeability to rainfall); by day they turn carbon dioxide into oxygen; they can provide organic matter suitable for building materials; and they help people mark time both by growth and by change with the seasons. Our associations with plants are mostly pleasant ones, and they contribute to the enjoyment of the places where they grow.

Plants are also of immediate practical value to the building designer because they can enhance privacy, slow the winter wind, reduce glare from strong sunlight, and/or prevent summer sun from entering and overheating buildings. In the last role, plants are particularly noteworthy, because they enhance a feeling of coolness when breezes rustle or sway their leaves. Most importantly, they respond more to cycles of outdoor temperature than to the cycles of sun position. Unlike fixed-position shading devices on buildings, plants provide their deepest shade in the hottest weather.

An overhang for south-facing windows at the Springs Preserve, shown in Fig. 3.40, is further illustrated by educational markers denoting the position of the sun at various times of the year. Maximum shade is provided at noon on the summer solstice. A typical approach to fixed sunscreen design in a U.S. temperate zone is to shade at least half of a south window in a residence (or all of a window in an office with internal heat loads) from March 21 to September 21 (vernal equinox to autumnal equinox). Yet, March is (on average) a colder month than September; March 21 is the last official day of winter, whereas September 21 is the last day of summer. Indeed, average monthly temperatures for June and September can be quite similar. Solar radiation is more welcome in early spring than in early fall, yet sun position is identical at these times.

In contrast to fixed sunscreens, deciduous plants do most of their shading from the middle of June to early October, giving windows access to solar radiation throughout much of the spring (Figs. 3.41, 3.42).

Deciduous trees have a potential disadvantage for solar heating, in that certain species (such as sweet gum and some oaks) hold on to their leaves well into the heating season, a tendency increased by fertilizing or irrigating near the tree. Other trees have a dense branch structure, blocking a surprisingly high percentage of solar radiation even when bare (Table 3.5). Agricultural extension services in most areas can provide information on the hardiness and average dates of defoliation for various tree species. For solar collection, avoiding trees or large

(*a*) (*b*)

Fig. 3.40 *Educational solar angles displayed (a) for a roof overhang at Springs Preserve, Las Vegas, Nevada; (b) Detail displaying the shade provided during the summer solstice. (© Alison Kwok; all rights reserved.)*

Fig. 3.41 *A deciduous tree as a naturally "smart" shading device. (Courtesy Tyler Mavichien.)*

shrubs within the area shown in Fig. 3.43 is recommended. In this *protected zone*, a deciduous vine on a trellis above a south-facing window is a better shading strategy.

Many large buildings have a relatively short heating season because they have substantial and consistent internal heat gains. For such internal-load (heat-dominated) buildings, a tree or vine that foliates early in spring, defoliates late in fall, and has low transmissivity in summer is advantageous. The choice of trees, shrubs, and vines to improve a site and/or building microclimate can best be made after a month-by-month analysis of specific building heating and cooling needs.

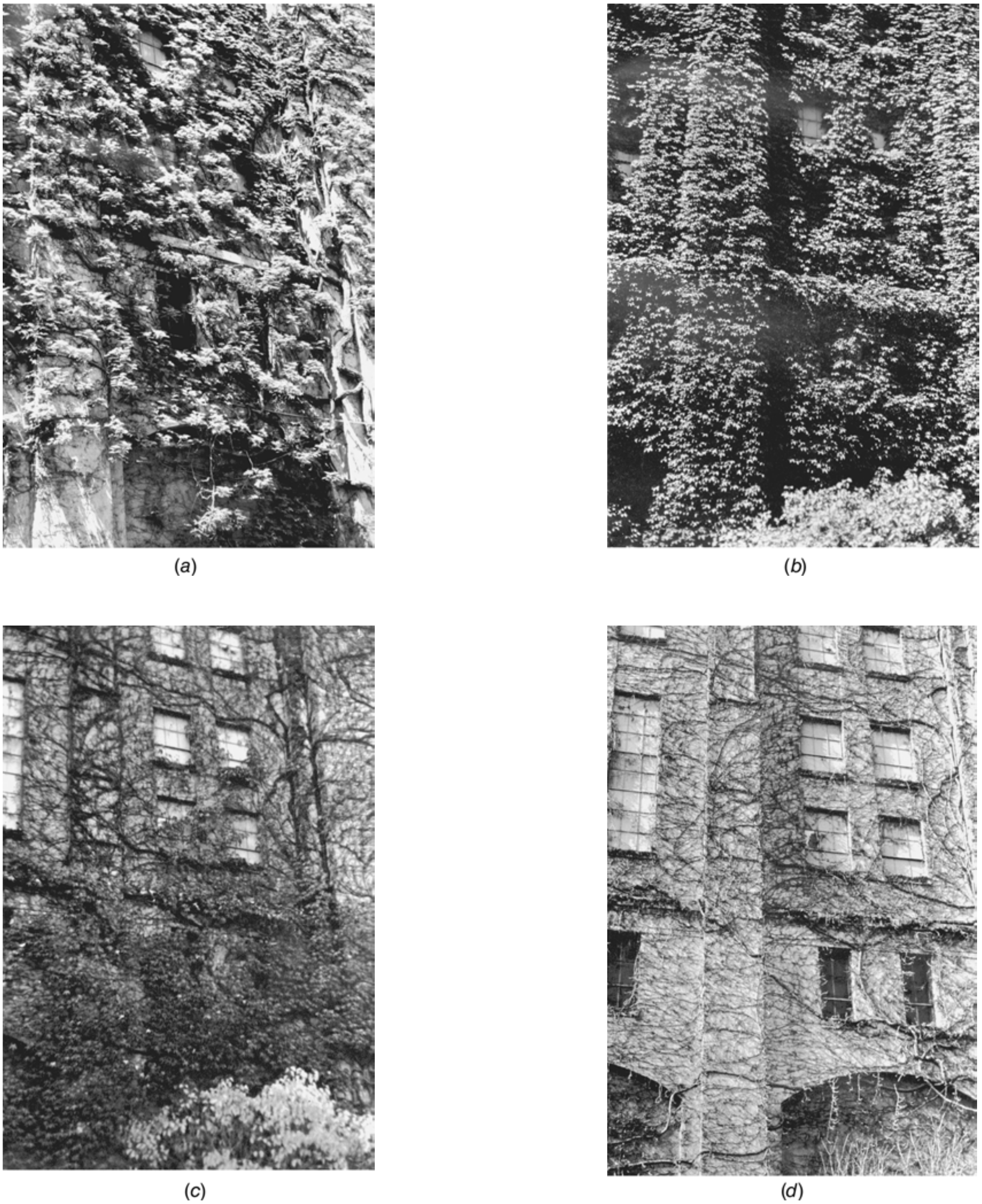


__Fig. 3.42__ Deciduous vines, temperature, and sun position. The sun's path through the sky is identical in late May (a) and late July (b). Similarly paired—but lower—sun paths occur in late November (c) and late January (d). This deciduous vine responds more to the temperature of its Oregon climate than to the sun's position, which makes it particularly useful as a sun control device. For pest control and wall longevity, it is best to keep vines on a trellis rather than on the wall surface. (From Reynolds, 1976.)

TABLE 3.5 Deciduous Trees for Summer Shading and Winter Solar Collection

		Transmissivity[a] Range %				Mature Height	
Botanical Name	**Common Name**	**Summer**	**Winter**	**Foliation[b]**	**Defoliation[c]**	**m**	**ft**
Acer platanoides	Norway maple	5–14	60–75	E	M	15–25	50–82
Acer rubrum	Red maple	8–22	63–82	M	E	20–35	65–115
Acer saccharinum	Silver maple	10–28	60–87	M	M	20–35	65–115
Acer saccharum	Sugar maple	16–27	60–80	M	E	20–35	65–115
Aesculus hippocastanum	Horse chestnut	8–27	73	M	L	22–30	72–98
Amelanchier canadensis	Serviceberry	20–25	57	L	M		
Betula pendula	European birch	14–24	48–88	M	M–L	15–30	50–98
Cercis canadensis[d]	Red bud	62	74	L	M	12	40
Carya ovata	Shagbark hickory	15–28	66			24–30	78–98
Catalpa speciosa	Western catalpa	24–30	52–83	L		18–30	60–98
Cornus florida[d]	Dogwood	43	53	L	E	11	36
Fagus sylvatica	European birch	7–15	83	L	L	18–30	60–98
Fraxinus pennsylvanica	Green ash	10–29	70–71	M–L	M	18–25	60–82
Gleditsia tricanthos inermis	Honey locust	25–50	50–85	M	E	20–30	65–98
Juglans nigra	Black walnut	9	55–72	L	E–M	23–45	75–148
Liquidambar styraciflua[d]	Sweet gum	33	47	M	L	24	78
Liriodendron tulipifera	Tulip tree	10	69–78	M–L	M	27–45	88–148
Platanus acerifolia	London plane tree	11–17	46–64	M–L		30–35	98–115
Populus detoides	Cottonwood	10–20	68	E	M	23–30	75–98
Populus tremuloides	Trembling aspen	20–33		E		12–15	40–50
Quercus alba	White oak	13–38					
Quercus palustris[d]	Pin oak	45	47	L	L	23	75
Quercus rubra	Red oak	12–23	70–81		M	23–30	75–98
Robinia pseudoacacia[d]	Black locust	38	40	L	E	21	69
Tilia cordata	Littleleaf linden	7–22	46–70	L	E	18–21	60–69
Ulmus americana	American elm	13	63–89	M	M	18–24	60–78

Source: Brown and Gillespie (1995), except as noted.

[a]Transmissivity to solar radiation; estimates vary with instruments used by various researchers.

[b]Foliation: E = early (before April 30); M = middle (May 1–15); L = late (after May 15).

[c]Defoliation: E = early (before November 1); M = middle (November 1–30); L = late (after November 30).

[d]From Montgomery (1987). Transmissivity % = (100% − blockage %).

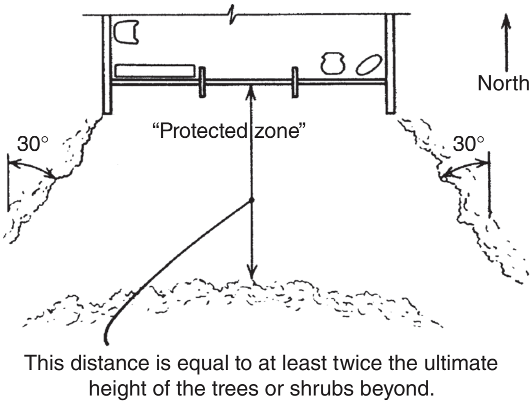


Fig. 3.43 *Protecting access to winter sun, given a lawn or terrace of limited size to the south of solar collecting surfaces. Coniferous and even deciduous plants within the "protected zone" should be avoided unless they are very low growing or are a reliably early defoliating species (see Table 3.5). Summer sun protection for such south-facing windows is best provided by flexible architectural controls such as awnings or hanging screens.*

3.10 CASE STUDY—SITE AND RESOURCE DESIGN

Aldo Leopold Legacy Center, Baraboo, Wisconsin

PROJECT BASICS

- Location: Baraboo, Wisconsin, USA
- Latitude: 43.52°N; longitude: 89.46°W; elevation: 974 ft (297 m)
- Heating degree days: 7673 base 65°F (4263 base 18.3°C); cooling degree days: 2389 base 50°F (1327 base 10°C) at Madison airport; annual precipitation 33.8 in. (858 mm)
- Building type: New construction; offices, meeting rooms, exhibit area
- Building area: 13,000 ft^2 (1208 m^2) [8644 ft^2 (803 m^2) conditioned space]
- Completed Spring 2007
- Client: Aldo Leopold Foundation
- Design team: The Kubala Washatko Architects, Inc. and consultants

Background. The Aldo Leopold Legacy Center is a Leadership in Energy and Environmental Design (LEED) Platinum certified project, the first such project ever earning 61 (of 69 possible) points and the first to earn a point for being a net-zero energy, carbon-neutral building. The site and its resources were integral components in achieving this aggressive design goal. This will be further discussed in the following sections to demonstrate the opportunities and resources that are on-site, free, and ready to be captured. The Aldo Leopold Foundation's (ALF) mission is to uphold the land ethic, and this unwavering goal helped to motivate the design team to exemplify the founding principles of the Foundation through innovation and sustainability. The Aldo Leopold Legacy Center utilizes a number of passive strategies and is constructed with local materials that were transported an average of 100 miles per pound (359 km per kg).

Context. The Aldo Leopold Legacy Center (ALLC) is an organization dedicated to promoting Aldo

Fig. 3.44 The Aldo Leopold Legacy Center in Baraboo, Wisconsin (north of Madison), which attained LEED Platinum certification. (© The Kubala Washatko Architects, Inc.; used with permission.)

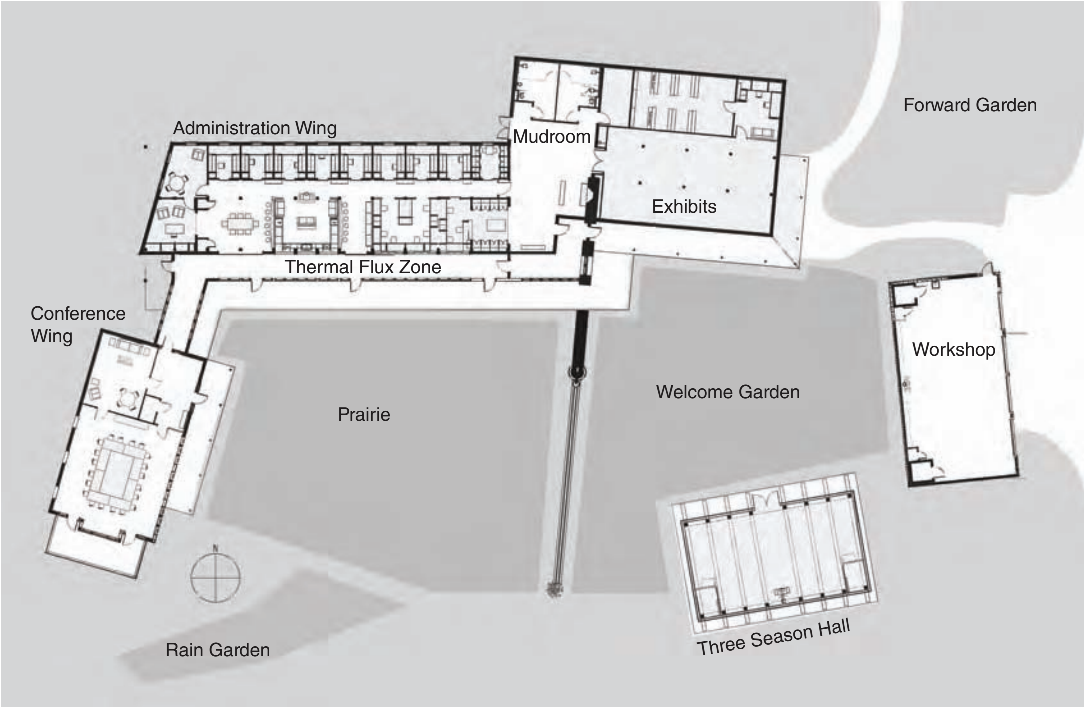


Fig. 3.45 *Site plan of the Aldo Leopold Legacy Center showing elongated buildings and southern orientation around a courtyard. (© The Kubala Washatko Architects, Inc.; used with permission.)*

Leopold's land ethic. Leopold, author of the *Sand County Almanac*, developed a belief that the term "community" should expand to include elements such as the "soils, waters, plants and animals, or collectively: the land." His writings set the stage for the modern conservation movement and particularly our current tendencies toward ecological thinking. An original building on the site, called the "Leopold shack," served as a retreat as well as a center for ecological research. Formerly a chicken coop, the shack was built primarily of found materials, used passive strategies for daylighting and ventilation, and required no electricity. Design of the new center retained the same ethic of conservation present in the shack, even with increased occupancy, energy demands, and building functions.

Design Intent. The ALLC is a direct reflection of Aldo Leopold's values. The leading principles (intent) behind the design included:

- Respect Aldo Leopold's land ethic in all aspects of design.
- All occupied zones are perimeter zones designed to use daylight and natural ventilation.
- Minimize electric lighting use during occupancy.
- Minimize HVAC systems use during occupancy.
- Minimize motive power in all piping and ductwork systems.
- Achieve a building energy demand goal of 17 kBtu per ft^2 per year (53.6 kWh per m^2 per year).
- Generate energy on site from solar radiation and biomass.
- Achieve carbon-neutral building operation.
- Utilize on-site wood resources in the building.

The center was built on land that was previously used for housing; hence. no new land was built upon. Ninety-thousand board feet (27,400 board meters) of wood harvested from nearby forests, including many red and white pines planted by Aldo Leopold himself in the 1930s, were used in the building. The smaller trees were kept "in the

Fig. 3.46 *Administrative center of the Aldo Leopold Legacy Center, with clerestories and daylight zoning throughout the building—strategies that helped to reduce the use of electric lighting. (© The Kubala Washatko Architects, Inc.; used with permission.)*

round," which allowed the sapwood, the strongest part of the wood, to remain intact. Each tree selectively harvested from the site was measured and its use within the building accounted for as part of the design process. Natural ventilation, daylighting, and passive solar heating strategies helped the center reach the carbon-neutral performance benchmark, although active systems are needed to meet the occupants' comfort needs during very cold and hot and humid conditions. Energy sources for the building include on-site photovoltaic panels, solar hot water collectors, and wood-burning heat sources. Radiant floors meet heating and cooling loads in the offices and exhibit space. Required ventilation air is tempered by earth tubes. Additional energy, if needed, is purchased from wind power providers. On a net annual basis, the ALLC is designed to produce 110% of the energy required for its operation.

Design Criteria and Validation. The project achieved a LEED Platinum rating, with an exceptionally high number of certification points. The project specifically earned a point in the Innovation and Design category for achieving carbon neutrality in building operation. To develop an appropriate energy use goal for the building, the design team researched energy consumption and production values for other buildings of similar size and function, and also calculated the amount of solar radiation available on the site, to match the potential for solar energy use with building needs. The design team set an EUI goal of 17 kBtu per ft^2 per year (53.6 kWh per m^2 per year) based on the performance of Woods Hole Research Center and the Schlitz Audubon Nature Center (both high-performing buildings). Using the program size at that time, 10,000 ft^2, the design team established a renewable energy production requirement of 50,000 kWh, which would require roughly 3000 ft^2 (278.7 m^2) of PV collectors.

Post-Occupancy Validation Methods. Energy modeling using the TRNSYS software package integrated with the CONTAM program was performed during the preliminary design phases.

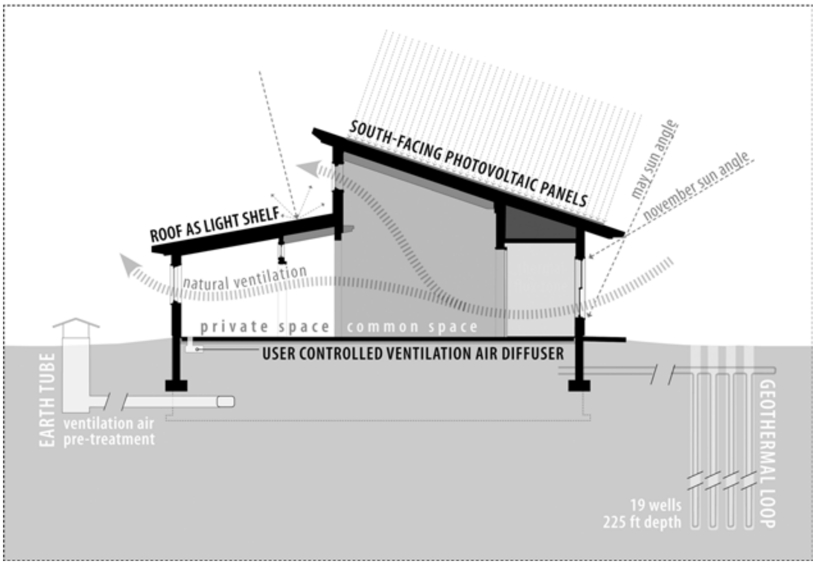


Fig. 3.47 *Building section showing strategies for lighting, heating, cooling, and ventilation. (© The Kubala Washatko Architects, Inc.; used with permission.)*

Performance monitoring has occurred since the building was completed. The building uses two energy sources: electricity and wood. Electricity is monitored by two installed meters that measure electricity produced on site (surplus given to the grid) and electricity consumed by the building.

The original design model suggested that the building would generate approximately more energy from on-site renewable energy than the building would require for operation. In its first year of operation, the building required approximately 4300 Btu per square foot per year (13.57 kWh/m^2) more than the renewable energy generation. A colder than normal winter, record annual snowfalls, snow cover on the PV array in January and February, higher plug loads than estimated, and some inverter issues in 2008 and 2011 are presumed to have caused the first year's performance gap and other slight shortfalls.

For the years 2008–2010 (Fig. 3.50), the simulated annual *net* energy flow is 0.51 kWh/ft^2 (5.4 kWh/m^2) per year. The actual net positive flow to the grid in years 2009, 2010, and 2012 was about 0.77 kWh/ft^2 (8.3 kWh/m^2) per year, which did well! Wood consumption has averaged half a cord of wood per year, contributing an equivalent EUI of 1.06 kBtu/ft^2 (3.34 kWh/m^2) per year (Utzinger and Swenson, 2012).

Although the building falls short of achieving net zero energy goals, the Foundation far surpasses carbon neutrality through the managed forests, which remove 110.1 metric tons of carbon dioxide from the atmosphere per year, more than offsetting the 46.99 metric tons of carbon dioxide emitted by the organization.

Performance Data. Information available to date suggests that the design team succeeded in upholding the Leopold legacy by utilizing on-site energy and resources:

- The building achieved a LEED Platinum rating.
- Total emissions: 45.3 metric tons of CO_2/yr
- Offset from renewable energies: -20.8 metric tons of CO_2/yr
- Forest sequestration: -29.1 metric tons of CO_2/yr
- Net result: -4.6 metric tons of CO_2/yr
- Half of all wood used in the building, 90,000 board feet (27,400 board meters), was harvested on site and milled 70 miles (112 km) away.

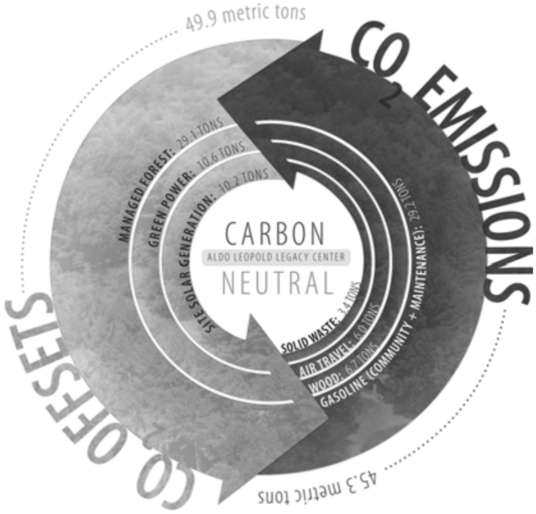


Fig. 3.48 *A carbon emissions diagram showing carbon neutrality: an annual balance of emissions versus offsets. (© The Kubala Washatko Architects, Inc.; used with permission.)*

- The building materials on average only traveled 100 miles per pound (359 km per kg) to the site.
- More than 95% of construction waste was recycled.
- The project is designed to meet the goals of the 2030 Challenge.
- The building uses 70% less energy than a typical building its size.
- The building was named an AIA COTE Top Ten Building for 2008.

(*a*)

(*b*)

Fig. 3.49 *(a) Trees selectively harvested from the site. (b) Accounting for each tree and placement of each board within the building. (© The Kubala Washatko Architects, Inc.; used with permission.)*

FOR FURTHER INFORMATION

The Aldo Leopold Foundation: www.aldoleopold.org/

Boehland, Jessica. "Building on Aldo Leopold's Legacy." *Green Source*, April 2008, pp. 80–85.

Chapa, Jorge. 2007. "First LEED Platinum Carbon Neutral Building!" Inhabitat: www.inhabitat.com/2007/11/08/first-leed-platinum-carbon-neutral-building/

Malin, Nadav. 2013. "Forest Ecology: Not quite net-zero, but carbon-neutral, thanks to a well-managed forest," *GreenSource*, March 2013. http://greensource.construction.com/green_building_projects/2013/1303-baraboo-wisconsin.asp

The Kubala Washatko Architects, Inc.: http://www.tkwa.com/

Utzinger, M. and S. Swenson. 2012. "The Aldo Leopold Legacy Center: Expanding the Definition of 'Community' in Carbon Management," 156–166 in Walleriser, A., N. Rajkovich, and J. Forester, *Planning Theory & Practice*, Vol. 13, No. 1, 113–174, March 2012.

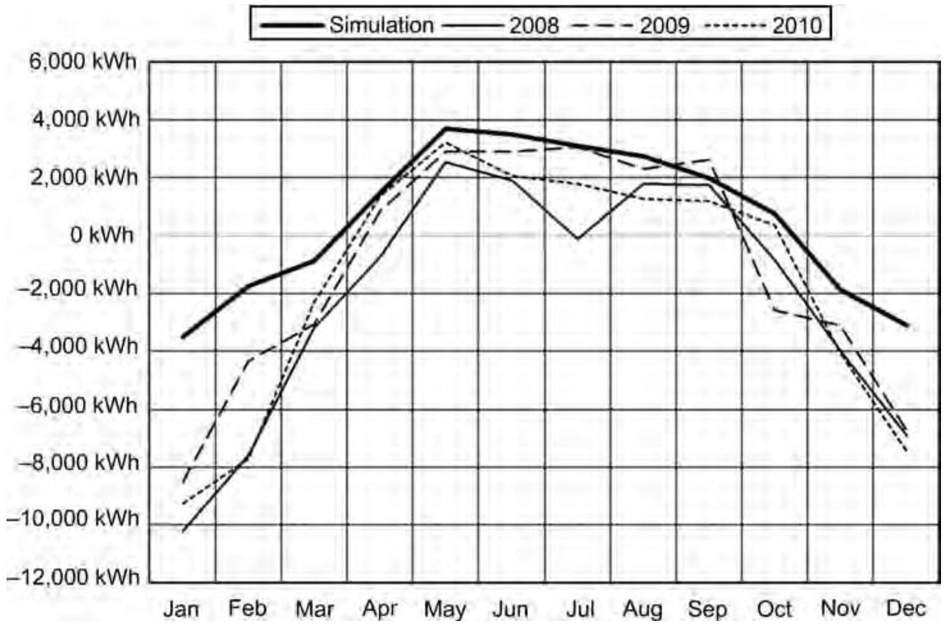


Fig. 3.50 *Simulated and actual monthly electrical energy use. (© D. Michael Utzinger; used with permission.)*

References and Resources

American Institute of Architects. 2013. Top Ten Metrics: Portland Community College Newberg Center. www.aiatopten.org/node/75

ASES. 1981. *Passive Cooling*. American Solar Energy Society. Boulder, CO.

Beranek, W. J. 1980. "General Rules for the Determination of Wind Environment," in *Wind Engineering*, J. E. Cermak (ed.). Pergamon Press. Elmsford, NY.

Bragdon, C. 1971. *Noise Pollution: The Unquiet Crisis*. University of Pennsylvania Press. Philadelphia, PA.

Brown, R. D. and T. J. Gillespie. 1995. *Microclimatic Landscape Design: Creating Thermal Comfort and Energy Efficiency*. John Wiley & Sons. New York.

Caulkins, Meg. 2012. *The Sustainable Sites Handbook: A Complete Guide to the Principles, Strategies, and Best Practices for Sustainable Landscapes*. John Wiley & Sons. Hoboken, NJ.

Cohen, S., D. C. Glass, and J. E. Singer. 1973. "Apartment Noise, Auditory Discrimination, and Reading Ability in Children." *Journal of Experimental Social Psychology*, Vol. 9, No. 5.

DeKay, M. 1992. "A Comparative Review of Daylight Planning Tools and a Rule-of-Thumb for Street Width to Building Height Ratio." *Proceedings of the 17th National Passive Solar Conference*, Cocoa Beach, FL. American Solar Energy Society. Boulder, CO.

Doelle, L. 1972. *Environmental Acoustics*. McGraw-Hill. New York.

Gandemer, J. 1977. "Wind Environment Around Buildings: Aerodynamic Concepts," in *Wind Effects on Buildings and Structures*, K. J. Eaton (ed.). Cambridge University Press. New York.

Graedel, T. E. and P. J. Crutzen. 1989. "The Changing Atmosphere." *Scientific American*, September 1989.

Harden, G. 1968. "The Tragedy of the Commons." *Science*, Vol. 162, no. 3859, December 13, 1968.

Knowles, R. 1981. *Sun, Rhythm, Form*. MIT Press. Cambridge, MA.

Landsberg, H. E. 1970. "Climates and Urban Planning," in *Urban Climates*. World Meteorological Organization Technical Note 108. Geneva.

Lawrence Berkeley National Laboratory, Heat Island Group: http://heatisland.lbl.gov/

Lowry, W. P. 1988. *Atmospheric Ecology for Designers and Planners*. Van Nostrand Reinhold. New York.

Lowry, W. P. and P. P. Lowry. 1995. *Fundamentals of Biometeorology, Volume 2: The Biological Environment*. Peavine Publications. McMinnville, OR.

Marsh, W. M. 1991. *Landscape Planning, Environmental Applications*, 2nd ed. John Wiley & Sons. New York.

Mazria, E. and D. Winitsky. 1976. *Solar Guide and Calculator.* Center for Environmental Research, University of Oregon. Eugene.

McPherson, E. G. (ed.). 1984. *Energy-Conserving Site Design*. American Society of Landscape Architects. Washington, DC.

Milne, Murray. "Energy Design Tools." University of California, Los Angeles. http://www.energy-design-tools.aud.ucla.edu/

Montgomery, D. 1987. "Landscaping as a Passive Solar Strategy," in *Passive Solar Journal*, Vol. 4, No. 1. American Solar Energy Society. Boulder, CO.

Olgyay, V. 1963. *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton University Press. Princeton, NJ.

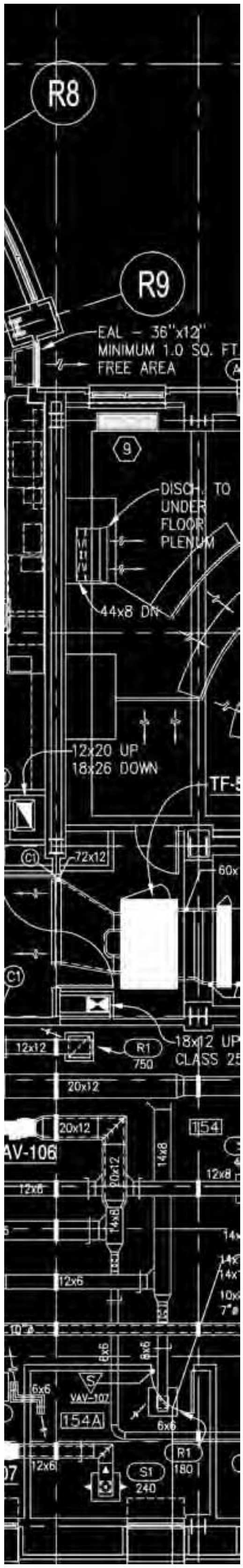
Reynolds, J. S. 1976. *Solar Energy for Pacific Northwest Buildings*. Center for Environmental Research, University of Oregon. Eugene.

U.S. Environmental Protection Agency, Global Warming Site. http://www.epa.gov/climatechange/index.html; Ozone Depletion Resources: http://www.epa.gov/docs/ozone/

Watson, D. and K. Labs. 1983. *Climatic Design.* McGraw-Hill. New York.

P A R T   I I

DESIGN FUNDAMENTALS



The chapters that compose Part II lay the foundation for design decisions from conceptual to design development. Often these topics—thermal comfort, indoor environmental quality, shading, and material considerations of the enclosure—can be a source of inspiration (or challenge). Chapter 4 discusses human thermal comfort, the variety of conditions that are generally deemed comfortable, and implications of a more broadly defined thermal comfort zone. Chapter 5 introduces the issue of indoor air quality, which is a major concern of building occupants and designers and a focus of green building design efforts. Chapter 6 discusses the principles and concepts of solar geometry, and offers guidance on the design of shading devices. And finally, the fundamentals of heat flow through various building enclosure elements are presented in Chapter 7.

CHAPTER 4

Thermal Comfort

ONE OF THE EARLIEST REASONS FOR BUILDING was to create shelter from often inhospitable climates and to attempt to enhance thermal comfort. This chapter addresses the interrelationships among human beings, ambient conditions, and conditions within the built environment. It begins by discussing heat flow to and from the body and then thermal comfort. Visual and acoustical comfort are dealt with later in the book; however, as will be seen, these important aspects of human response are not nearly as well-developed as thermal comfort. Other aspects of comfort, such as ergonomics and our response to spatial geometries, are beyond the scope of the book.

4.1 THE BODY AND HEAT

Across the full range of diverse daily activities, the human body is continuously generating heat as a byproduct of metabolism. The conversion of energy inputs (food) to work output is not terribly efficient, resulting in waste heat production. Because the body's core temperature must stay within a narrow range, we nearly always need to lose heat to our environment. The rate at which we produce heat changes frequently (with activity level), as does the surrounding environment's ability to accept heat. We have three common layers that act as interfaces between our core body conditions and the ambient environment. These layers act to regulate our body's heat loss. The first layer is our skin; the second layer is our clothing; the third layer is a building enclosure. The relative importance of these layers varies with the thermal conditions we confront, and with our desire to be free to select clothing ensembles that respond to other than thermal demands.

(a) Metabolism

The rate at which we generate heat (the metabolic rate) depends mostly upon our level of muscular activity, partly upon what we eat and drink (and when), and partly on where we are in our normal daily cycle. Our heat production is measured in metabolic (met) units (Table 4.1). One met is defined as 50 kcal/h m^2 (equal to 18.4 Btu/h ft^2 or 58.2 W/m^2). One met is the energy produced per unit of surface area by a seated person at rest. Under these conditions, the total heat produced by a normal adult is about 360 Btu/h (106 W). The more active we are, the more heat we produce.

There are a number of interactions between our skin and the rest of our body. These include the sense of touch, the circulation of blood, and the exchange of water vapor. The sensations of touch include pressure and pain as well as heat and cold. The experiences of heat and cold are produced by contact with building or object surfaces and by immersion in air, as well as by radiation. These sensations frequently signal impending shifts in bodily heat regulation, a process that is controlled by the portion of the brain called the *hypothalamus*.

TABLE 4.1 Metabolic Rates for Typical Tasks

	Metabolic Rate[a]		
Activity	**met units[b]**	**Btu/h ft²**	**W/m²**
Resting			
Sleeping	0.7	13	40
Reclining	0.8	15	45
Seated, quiet	1.0	18	60
Standing, relaxed	1.2	22	70
Walking (on the level)			
2 mph (0.9 m/s)	2.0	37	115
3 mph (1.2 m/s)	2.6	48	150
4 mph (1.8 m/s)	3.8	70	220
Office activities			
Reading, seated	1.0	18	60
Writing	1.0	18	60
Typing	1.1	20	65
Filing, seated	1.2	22	70
Filing, standing	1.4	26	80
Walking about	1.7	31	100
Lifting, packing	2.1	39	120
Driving/flying			
Car	1.0–2.0	18–37	60–115
Aircraft, routine	1.2	22	70
Aircraft, instrument landing	1.8	33	105
Aircraft, combat	2.4	44	140
Heavy vehicle	3.2	59	185
Miscellaneous occupational activities			
Cooking	1.6–2.0	29–37	95–115
Housecleaning	2.0–3.4	37–63	115–200
Seated, heavy limb movement	2.2	41	130
Handling 110-lb (50-kg) bags	4.0	74	235
Pick and shovel work	4.0–4.8	74–88	235–280
Machine work			
Sawing (table saw)	1.8	33	105
Light (electrical industry)	2.0–2.4	37–44	115–140
Heavy	4.0	74	235
Miscellaneous leisure activities			
Dancing, social	2.4–4.4	44–81	140–255
Calisthenics/exercise	3.0–4.0	55–74	175–235
Tennis, singles	3.6–4.0	66–74	210–270
Basketball	5.0–7.6	90–140	290–440
Wrestling, competitive	7.0–8.7	130–160	410–505

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]For average adult with a body surface area of 19.6 ft² (1.8 m²). For whole-body average heat production, see also Table G.8.

[b]One met = 18.4 Btu/h ft² = 58.2 W/m².

The hypothalamus triggers changes in our blood circulation patterns in response to signals from our skin and changes in our core body temperature. If the body temperature is dropping (we are cold), the rate of heat loss from the body needs to be reduced. This is accomplished through a decrease in the flow of blood from the core toward the surface of the skin. This decrease in blood flow toward the surface is called *vasoconstriction*, and is triggered in part by temperature (cold) signals from our skin. Blood carries heat around the body, and reduced flow to the extremities under cold conditions reduces heat loss. Under this condition, our sweat glands also force less water to the skin surface, which reduces evaporation and thus heat loss.

Note the implications of this zoning arrangement. We strive to maintain, at all costs, a nearly constant core temperature for our vital organs. This protected zone takes thermal precedence over the less vital extremities zone, including the arms and legs and then the fingers and toes. The farther from our central body mass (fingers and toes) and the greater the surface area (ears), the more and faster the temperature will drop in cold conditions. The most variable thermal zone is our skin surface.

When cold conditions worsen, we get goosebumps, symptoms of our skin's unsuccessful attempt to create insulation by fluffing up our body hair. Because we cannot add insulation this way, we soon increase our metabolic rate, or burn more fuel, by shivering, muscular tension, or increased muscular activity. At the point where shivering incapacitates us, we may reach 6 met. Before this point, we seek help from our second and then our third skins of clothing and buildings.

The opposite occurs when we are too hot: first, blood flow toward the skin surface increases (*vasodilation*), triggered primarily by warm signals from our core. The sweat glands greatly increase their secretion of water and salt to the skin surfaces. This increases heat loss by evaporation (although salt accumulations impede evaporation by lowering the vapor pressure of water).

(b) Heat Flow

Once blood and water transport our surplus heat to the skin surface, we have four ways to pass it to the environment: *convection* (air molecules contact our body, absorbing heat), *conduction* (we touch cooler surfaces, and heat is transferred), *radiation* (when our skin surface is hotter than other surfaces "seen" but not touched, heat is radiated to these cooler surfaces, and vice versa when other surfaces are hotter than our skin surface), and *evaporation* (a liquid can evaporate only by removing large quantities of heat from the surface it is leaving). The amount of heat we lose by each of these four methods depends

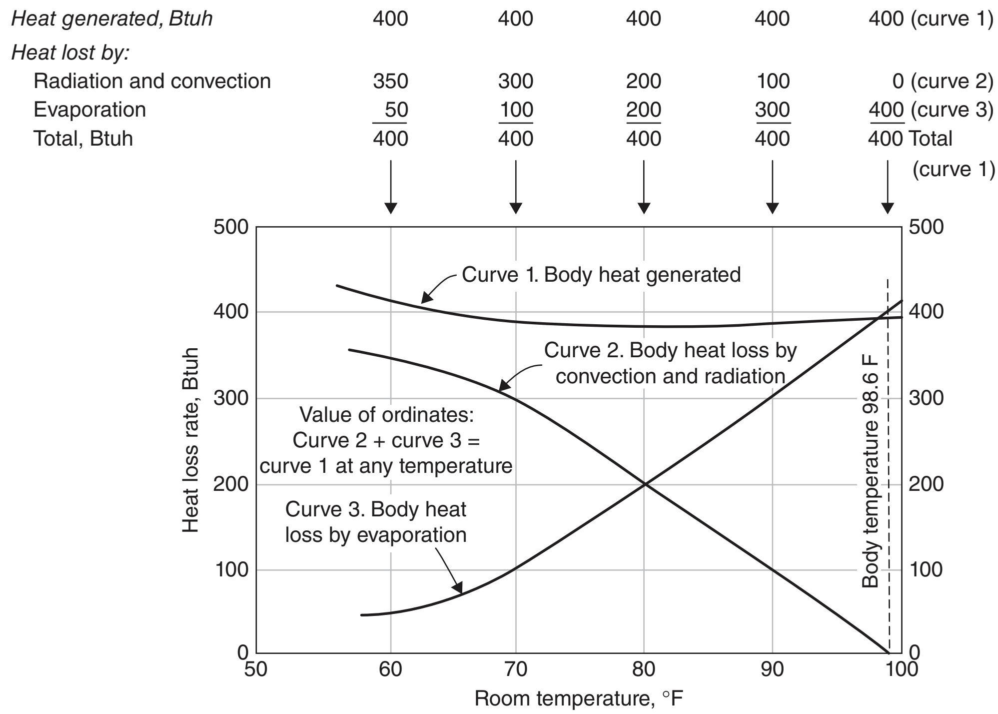


Fig. 4.1 *Heat generated and lost (approximate) by a person at rest (with 45% relative humidity).*

upon the interactions among our metabolism, our clothing, and our environment. Figure 4.1 illustrates the typical situation of a person at rest as environmental conditions change.

As surrounding air and surface temperatures approach our skin temperature, we lose the options of convection, conduction, and radiation. Evaporation becomes essential, so access to dry, moving air is greatly appreciated. As air and surface temperatures fall, evaporation decreases while convection, conduction, and particularly radiation increase. Under the normally comfortable temperature of 70°F (18°C), the proportions of body heat loss per hour are as shown in Table 4.2.

TABLE 4.2 Approximate Heat Loss Distribution under Comfort Conditions

Radiation, convection, and conduction	72%
Evaporation	
From skin surface	15%
From lungs (exhaled air)	7%
Warming of air inhaled to lungs	3%
Heat expelled in feces and urine	3%

(c) Clothing

Usually clothing acts as an insulating layer and is particularly effective at retarding radiation, convection, and conduction. As air and surface temperatures in our environment fall well below our body's temperature, the clothing provides a second skin and increased insulation. In hot and humid environments, our bodies need moving air against the skin to remove heat, while clothing provides protection from the sun's radiant heat. In hot and arid environments, clothing layers can prevent our bodies from losing too much water, and also provide shading to our skin.

The insulation value provided by clothing is measured in clo units, where 1 clo is equal to 0.88 ft^2 h F/Btu (0.155 m^2 K/W). The total clo of a person's attire may also be estimated by simply adding the clo of each item from Table 4.3; this total will be a bit higher than the actual clo value of the ensemble. The total clo can also be estimated by assuming 0.15 clo/lb (0.35 clo/kg) of clothing weight. Sometimes the position of clothing is as important as its clo value; consider the role of

TABLE 4.3 Typical Insulation Values for Clothing Ensembles

Ensemble Description[a]	clo[b]
Walking shorts, short-sleeve shirt	0.36
Trousers, short-sleeve shirt	0.57
Trousers, long-sleeve shirt	0.61
Same as above, plus suit jacket	0.96
Same as above, plus vest and T-shirt	1.14
Trousers, long-sleeve shirt, long-sleeve sweater, T-shirt	1.01
Same as above, plus suit jacket and long underwear bottoms	1.30
Sweatpants, sweatshirt	0.74
Long-sleeve pajama top, long pajama trousers, short 3/4-sleeve robe, slippers (no socks)	0.96
Knee-length skirt, short-sleeve shirt, pantyhose, sandals	0.54
Knee-length skirt, long-sleeve shirt, full slip, pantyhose	0.67
Knee-length skirt, long-sleeve shirt, half slip, pantyhose, long-sleeve sweater	1.10
Same as above; replace sweater with suit jacket	1.04
Ankle-length skirt, long-sleeve shirt, suit jacket, pantyhose	1.10
Long-sleeve coveralls, T-shirt	0.72
Overalls, long-sleeve shirt, T-shirt	0.89
Insulated coveralls, long-sleeve thermal underwear, long underwear bottoms	1.37

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]All ensembles include shoes and briefs or panties. All ensembles except those with pantyhose include socks, unless otherwise noted.

[b]One clo = 0.88 ft^2 h °F/Btu = 0.155 m^2K/W.

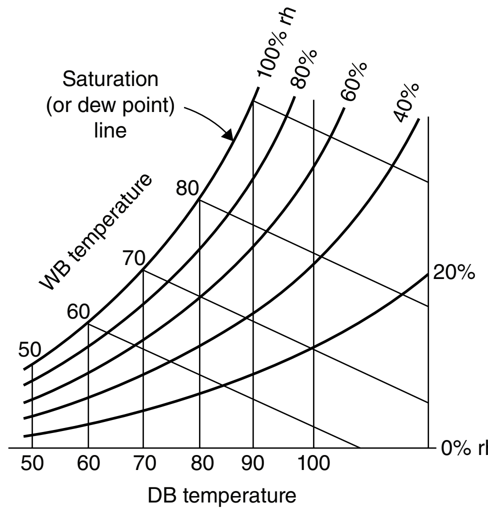


Fig. 4.2 *Some basic components of the psychrometric chart: DB and WB temperatures and RH.*

socks as they separate our feet from contact with a cold floor.

Our second skin (clothing) is just as likely as our third (building) skin to be more dominated by considerations of style than of thermal regulation; we cannot always count on our clothing—or buildings—to increase our thermal comfort.

4.2 PSYCHROMETRY

Moisture, air, and heat interact with some consequences that are threats to, and other consequences that are opportunities for, building performance. In winter, condensation within insulation due to falling air temperatures can be disastrous. In summer, adding moisture to hot, dry air can lower its dry-bulb (DB) temperature while raising its humidity to more comfortable levels.

These moisture, air, and heat interactions are complex. As air temperature rises, its capacity to hold moisture rises also, and the warmer air becomes less dense. These combined interactions are described by *psychrometry*, the study of moist air. Fortunately, these interactions can be combined within a single chart—see Fig. G.1 (I-P units) and Fig. G.2 (SI units).

Dry-bulb (DB), *wet-bulb* (WB) and *relative humidity* (RH) elements are combined in the schematic chart of Fig. 4.2, where the term *saturation line*, at 100% RH, is introduced. This is also called the *dew point* (DP) because dew forms (water vapor condenses) when saturated air touches any surface at or below the air's dew point temperature. This saturation is sometimes undesirable, as within walls or roofs, or on ceiling, air duct, or glass surfaces. However, it is often desirable, as on air-conditioner coils, where the resulting reduction of the moisture content in the air is deliberate.

The psychrometric chart may be used to graph a wide variety of processes, which are summarized in Fig. 4.3. To understand these processes, we must add to the basic chart of Fig. 4.2. The first addition is the *humidity ratio*, which indicates the amount of moisture by weight within a given weight of dry air. Air treatment processes that travel along these horizontal lines of constant humidity ratio (Fig. 4.4) are the familiar processes of simple heating (air passing through the heating coil of a furnace or through a solar collector) and simple (sensible) cooling (air passing through the cooling coil of an air conditioner before saturation). The humidity ratio is used in calculating latent heat gains from outdoor air.

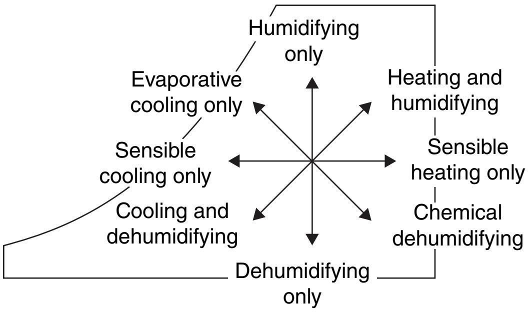


Fig. 4.3 *Climatic-conditioning processes expressed on the psychrometric chart. Adapted from "Architectural Design Based on Climate," by M. Milne and B. Givoni, in Watson (ed.),* Energy Conservation in Building Design. *Reprinted with the permission of the publisher, McGraw-Hill, Inc.*

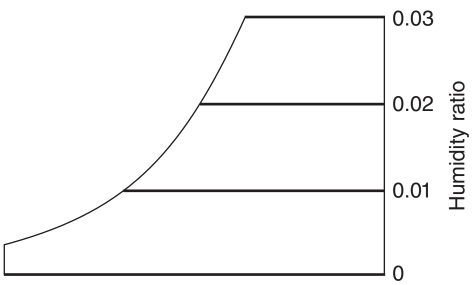


Fig. 4.4 *Humidity ratio on the psychrometric chart: I-P units are lb moisture/lb of dry air; SI units are kg moisture/kg dry air.*

The next addition shows how the *density* of air varies as its temperature and moisture content vary. These lines are those of *specific volume*, the reciprocal of density, a useful quantity in air-conditioning calculations and helpful in understanding the stack effect in passive design. The specific volume is given in ft^3/lb (m^3/kg) of dry air. From these lines in Fig. 4.5 it can be seen that a pound of hot air is larger

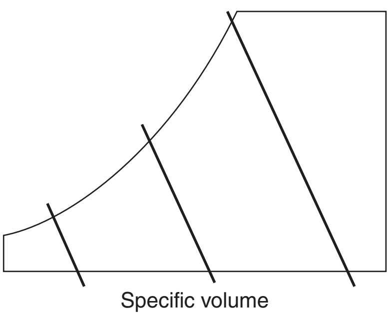


Fig. 4.5 *Specific volume on the psychrometric chart: I-P units are ft^3/lb dry air; SI units are m^3/kg dry air.*

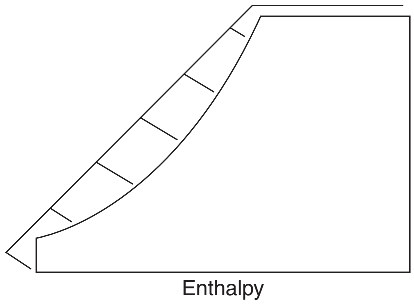


Fig. 4.6 *Enthalpy on the psychrometric chart: I-P units are Btu/lb; SI units are kJ/kg.*

(has more volume) than a pound of cold air. This larger volume per unit of weight increases buoyancy; thus, hot air rises, whereas cold air sinks.

The next addition (Fig. 4.6) involves *enthalpy*, the sum of the sensible and latent heat content of an air–moisture mixture relative to the sum of the sensible and latent heat in air at 0°F (0°C in SI units) at standard atmospheric pressure. Enthalpy units are Btu/lb (kJ/kg) of dry air. Enthalpy lines are almost parallel to those of WB temperature. Perhaps the most familiar process to travel along the lines of constant enthalpy is evaporative cooling, whereby increased moisture and lower air DB temperature are obtained *without changing the enthalpy* (total heat content) of the air. There is indeed a drop in sensible heat as the temperature drops, but this is matched by an increase in latent heat as the moisture content increases. The opposite process is chemical (desiccant) dehumidifying, whereby decreased moisture content is obtained at the price of increased air DB temperature; again, no change in enthalpy (total heat) occurs.

4.3 THERMAL COMFORT

A positive definition of comfort is "a feeling of well-being." The more common experience of comfort is simply a lack of discomfort—thermally, of being unconscious of how you are losing heat to your environment. ASHRAE (2013) defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation." There are three categories of factors that affect comfort: personal, measurable environmental, and psychological. Most *personal* factors are under your control: metabolism and clothing, as well as various behavioral adaptations such as migration to a more comfortable place, or drinking or eating warm or cold foods. *Measurable environmental* factors are the familiar tools of the designer: air temperature, radiant temperature, air motion, and humidity. *Psychological* factors are also familiar designers' tools, but they are difficult to quantify for comfort: color, texture, sound, light, movement, and aroma. These factors are often overlooked as we strive to meet the numerical (therefore calculable) physical criteria for thermal comfort. However, our primary design intent is to make people comfortable, and all aspects of buildings are our means to that end.

Consider the courtyard in a hot, dry climate (Fig. 4.7). Its fountain suggests coolness by the color and texture of its water; running water provides splashing sounds and sparkles of light and may generate some air motion. Vines provide shade, and their leaves sway in the slightest breeze, evidence of at least some air motion. Blossoms of flowering plants yield a cool fragrance that blends with the aroma of moistened surfaces in hot, dry surroundings. The measured coolness of such a courtyard may be but a slight improvement over the environment beyond, but it seems cool.

Then consider a fireplace in a cold climate (Fig. 4.8). The fire's color is intensely warm, and it dances and casts a flickering light; it crackles, and it yields a smoky aroma (not appreciated by all). Few textures seem hotter than that of glowing coals. Yet a fireplace might add but slightly to the overall warmth of a room, because it draws in cold air to replace the air that passes up the chimney. We seek a place near the fire for the real radiant warmth, but also for the psychological comfort the fire offers.

Fig. 4.7 *Indicators of coolness in a courtyard in Savannah, Georgia, include running water and shade from trees that move with the breeze. The senses of sight, hearing, touch, smell, and taste all may be involved in a perception of coolness. (© Alison Kwok; all rights reserved.)*

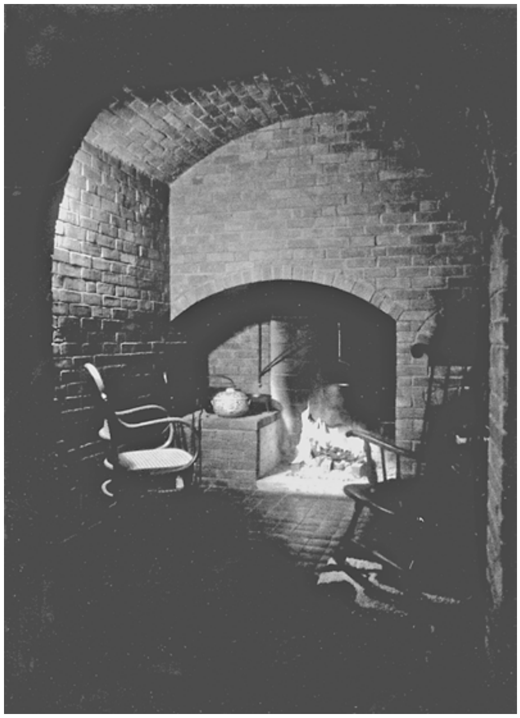


Fig. 4.8 *The open fire seems the very spirit of warmth, despite the heat lost by large quantities of exhaust air up the chimney. The senses of sight, hearing, touch, and smell all may be involved in a perception of warmth, wrapped in this red-brick environment. (Courtesy of the architect and photographer, Edward Allen.)*

In our society, designers are encouraged to take numerical data quite literally. The measurable environmental factors have been tested extensively in laboratories—but they exclude other factors. A holistic view of designing for comfort considers numbers as a nonabsolute guide; common sense and a designer's own thermal experience play important roles as well. Lisa Heschong's *Thermal Delight in Architecture* (1979) is an excellent expression of these points of view.

Ultimately, our buildings will be expected to demonstrate success with regard to the measurable environmental factors of comfort. Building environments and materials respond to the interactions of environmental factors via various mechanisms

TABLE 4.4 Environmental Factors Influencing Heat Transfer

Heat Transferred by:	Primarily Dependent upon:
Conduction	Surface temperature
Convection	Air temperature, air motion, humidity
Radiation	Surface temperature, orientation to the body
Evaporation	Humidity, air motion, air temperature

of heat transfer. Table 4.4 shows how air and surface temperatures, air motion, and humidity are related to heat transfer.

These comparisons are of primary importance in hot conditions, where humidity will influence the effectiveness of heat transfer mechanisms. For example, humidity is critical in hot dry environments dominated by evaporative heat loss. In cold conditions, heat loss by convection, radiation, and conduction is dominant, so humidity is less influential. Comfort studies have shown that skin temperature is an important factor in cold conditions, whereas skin wettedness (percentage covered by water) is most important in hot conditions.

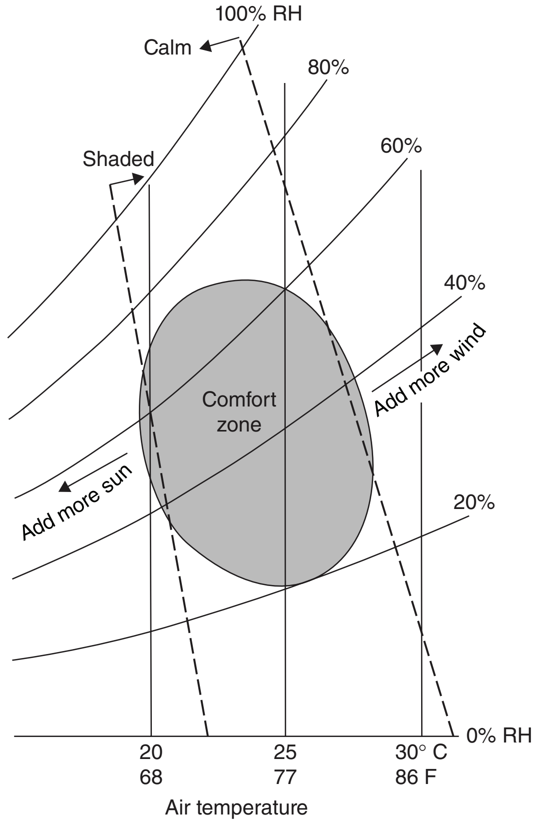


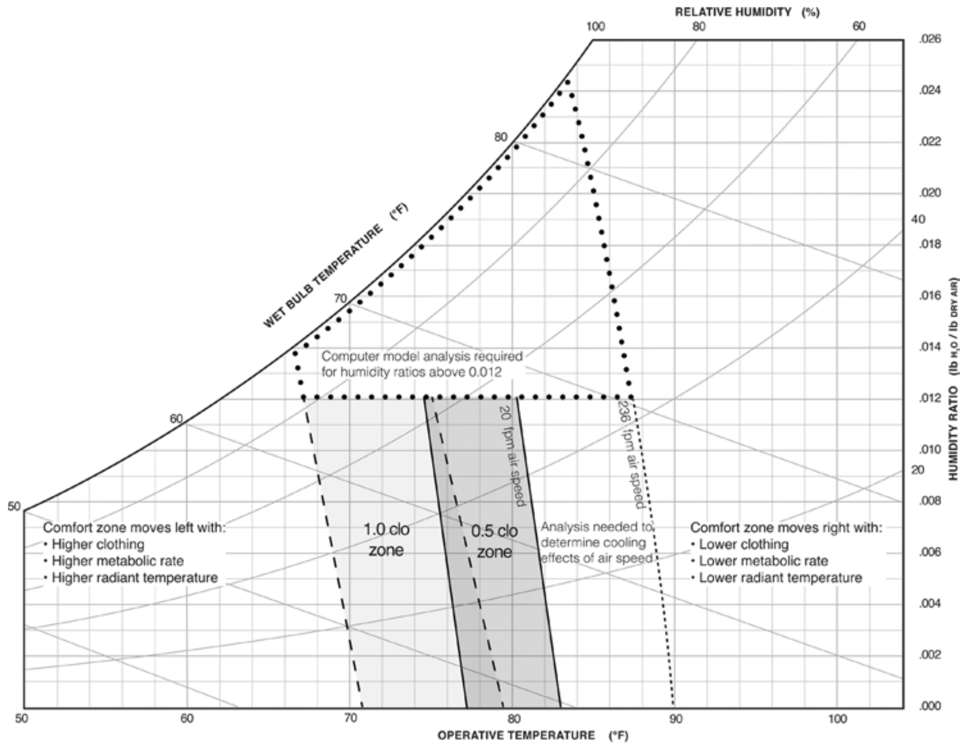
Fig. 4.9 *Comfort zone defined by relative humidity and air temperature.*

(a) Comfort Standards

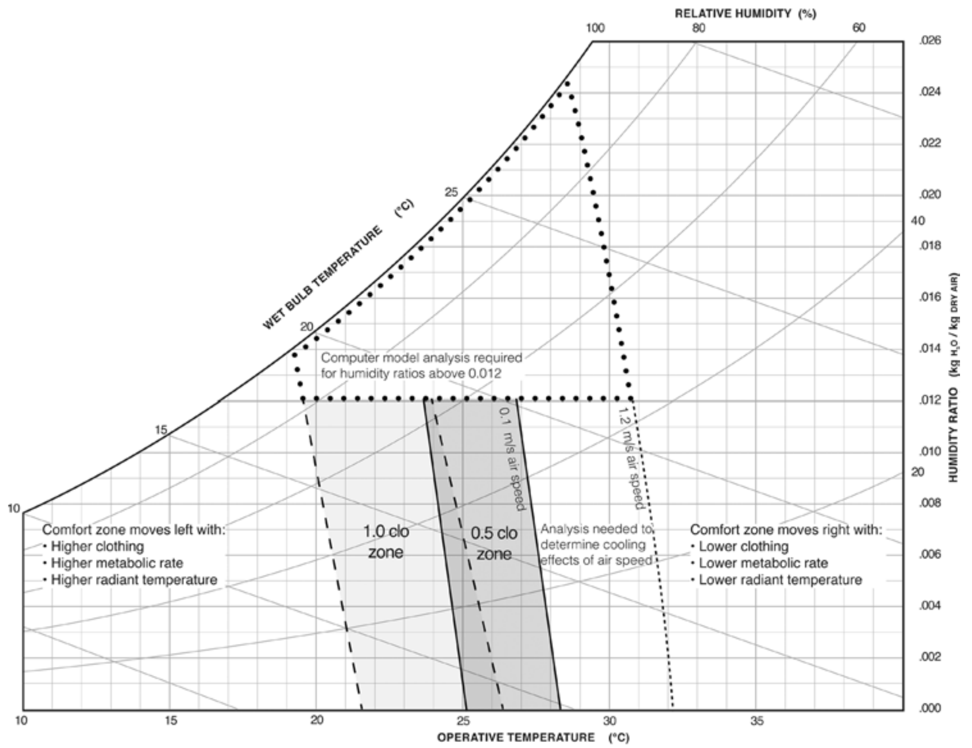
The concept of a comfort zone is diagrammed in Fig. 4.9, where surface temperatures are assumed to be not markedly different from air temperatures. Moving to the left of this zone, at lower air temperatures, comfort is still attainable if added radiant heat is provided—such as by increasing surface temperatures or providing exposure to the sun. Higher activity and more clothing would also help achieve comfort. Similarly, moving to the right of the comfort zone (at higher air temperatures), comfort is still attainable by increasing air motion (such as by exposure to wind), lowering the activity level, and removing clothing. In both directions limits are soon reached, but the important point is that the basic comfort zone can be expanded by changing environmental variables and/or human behavior.

The human thermal response, perceived as thermal comfort or discomfort, is shaped by six primary factors: metabolic rate (met), clothing insulation (clo), air temperature, radiant temperature, air speed, and relative humidity. The first two factors are personal variables of the occupants, and the remaining four are characteristics of the thermal environment. These variables can be measured directly or derived from other measurements (using a psychrometric chart where physical properties of moist air and related thermodynamic processes are graphically expressed).

Figure 4.10 (*a* and *b*) shows the thermal comfort zone as defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), where acceptable ranges of operative temperatures (T_{op}) and relative humidity are given for sedentary (1.0–1.3 met) persons wearing typical clothing (between 0.5 and 1.0 clo). Figure 4.10 specifies the comfort zone parameters with 80% occupant acceptability for the range of operative temperature and relative humidity, and air speeds no greater than 40 ft/min (0.20 m/s). Two zones are shown—one for 0.5 clo of clothing insulation (assumed worn when the outdoor environment is warm) and one for 1.0 clo of insulation (for when the outdoor environment is cool). Figure 4.10*c*



(*a*)



(*b*)

Fig. 4.10 *(a, b) ANSI/ASHRAE Standard 55-2013 comfort zone. (c) Relationships between increasing air speeds and temperature relative to thermal comfort. (Reprinted with permission; ©ASHRAE, ANSI/ASHRAE Standard 55-2013,* Thermal Environmental Conditions for Human Occupancy.*)*

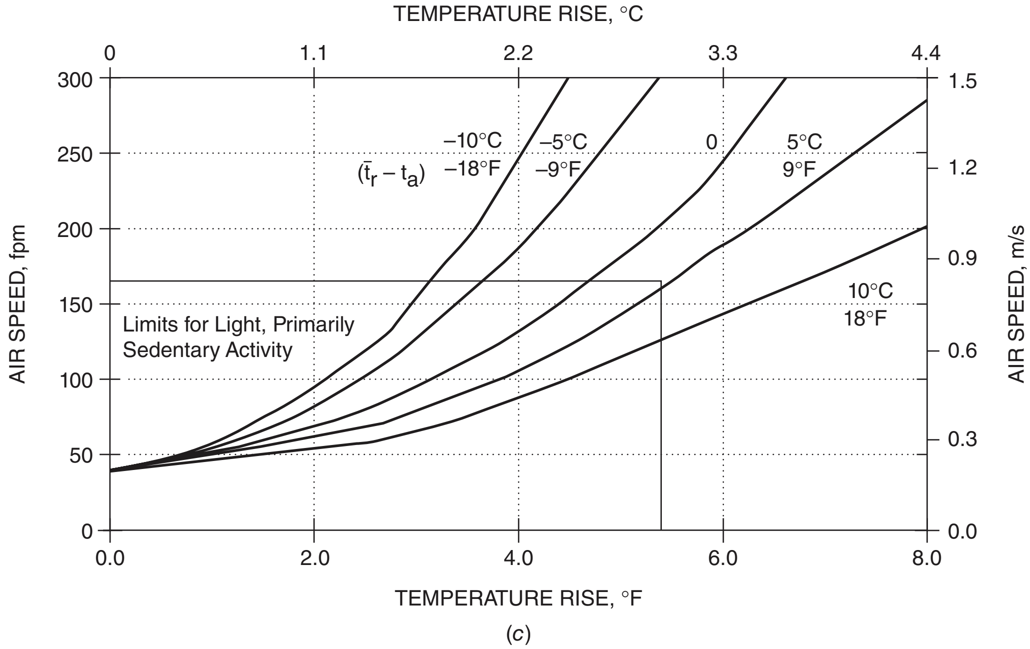


Fig. 4.10 *(continued)*

suggests the effect of increased air speeds on thermal comfort. The thermal comfort variables used here are defined as follows:

Dry-bulb (DB) temperature. DB temperature is the ambient air temperature as measured by a standard thermometer, thermocouple, or resistance temperature device. DB temperature can be used in combination with globe temperature and air velocity to calculate mean radiant temperature. Temperature affects comfort in a number of ways and, in combination with the other parameters described in this section, is a key factor in our energy balance, thermal sensation, comfort, discomfort, and perception of air quality.

Operative temperature. This is the average of the dry-bulb temperature and the mean radiant temperature (MRT).

Wet-bulb (WB) temperature. WB temperature is measured by a thermometer with a wetted bulb rotated rapidly in the air to cause evaporation of its moisture—as with the sling psychrometer shown in Fig. 4.11. In dry air the moisture readily evaporates and draws heat out of the thermometer to produce a lower temperature reading, called the *wet-bulb depression* (the difference between DB and WB temperatures). A large depression is indicative of low relative humidity (RH). Less evaporation, as when the air is already moisture-laden, results in a small wet-bulb depression and indicates high RH. Note that at 100% RH, DB and WB temperatures are equal.

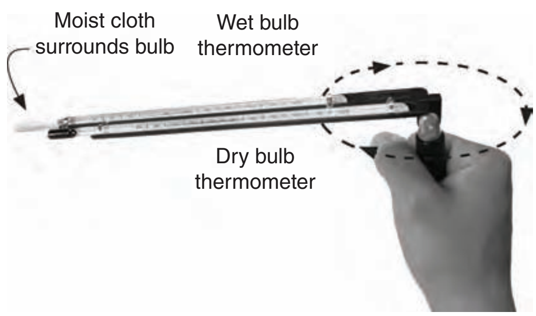


Fig. 4.11 *Sling psychrometer and its usage. Air motion encourages evaporation from the moist cloth, lowering the wet-bulb temperature below the surrounding air temperature, whereas the dry-bulb temperature stays constant at the surrounding air temperature. (At 100% RH, WB and DB temperatures will be equal.)*

Relative humidity may be measured directly or derived from DB and WB temperatures, and is the ratio of the actual density of water vapor in air to the maximum density of water vapor that such air could contain, at the same temperature, if it were 100% saturated.

Mean radiant temperature (MRT). The radiant temperatures of surrounding surfaces influence human comfort. With respect to the human body at a particular location, *mean radiant temperature* is defined as the uniform temperature of an imaginary surrounding enclosure in which radiant transfer from the human body would equal the radiant heat transfer in the actual nonuniform enclosure (ASHRAE 2013). MRT is a calculated variable and cannot be directly measured. One calculation approach involves using a globe thermometer, which can be easily constructed using a hollow sphere (e.g., a ping pong ball) with a thermocouple or thermometer bulb at its center. Equation 4.1, for determining MRT ($\bar{t}_r$) from globe temperature, is as follows (ASHRAE 2013). A quick graphical method of calculation is offered in Fig. 4.12:

I-P units: $\bar{t}_r =$

$$\left[(t_g+460)^4+\frac{4.74\times10^7 V_a^{0.6}}{\varepsilon D^{0.4}}(t_g-t_a)\right]^{0.25}-460 \tag{4.1}$$

SI units: $\bar{t}_r =$

$$\left[(t_g+273)^4+\frac{1.10\times10^8 V_a^{0.6}}{\varepsilon D^{0.4}}(t_g-t_a)\right]^{0.25}-273$$

where

$\bar{t}_r$ = mean radiant temperature, °F (°C)

t_g = globe temperature, °F (°C)

V_a = air velocity, fpm (m/s)

t_a = air temperature, °F (°C)

D = globe diameter, ft (m)

ε = globe emissivity (dimensionless)

Another calculation approach involves the geometry of the room relative to a specific point and uses Equation 4.2 (Egan, 1975):

$$\text{I-P or SI units } \bar{t}_r = \frac{\sum t\alpha}{360} = \frac{t_1\alpha_1+t_2\alpha_2+t_3\alpha_3+\ldots t_n\alpha_n}{360} \tag{4.2}$$

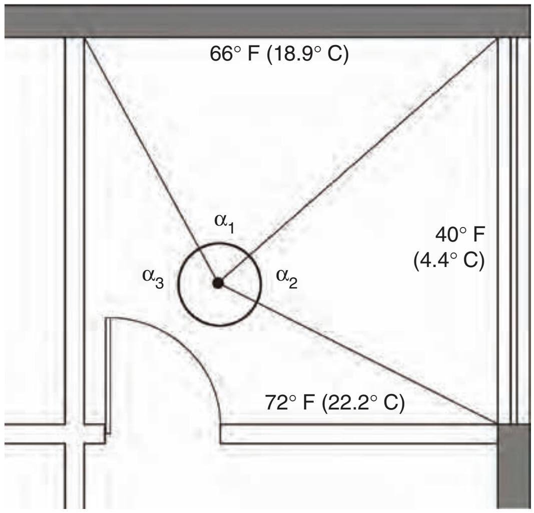


Fig. 4.12 *Graphic method of calculation for mean radiant temperature using the geometry of the room relative to a particular location. Using Equation 4.2, the surface temperature of the wall or window is multiplied by the exposure angle relative to the occupant's location. (Drawn by Tyler Mavichien; © 2013 Alison Kwok, all rights reserved.)*

where

$\bar{t}_r$ = mean radiant temperature, °F (°C)

α = surface exposure angle (relative to the occupant) in degrees

DB air temperature by itself is usually not an adequate comfort indicator, especially in passively solar-heated or passively cooled spaces, where radiant temperature or air motion may be more influential than air temperature. Occupants of naturally ventilated buildings, for example, seem to find comfortable a combination of higher temperatures and RH than do occupants of sealed, air-conditioned buildings. Figure 4.13 shows a much higher incidence of these warmer, more humid environments in Hawaiian naturally ventilated classrooms than in similar air-conditioned classrooms. Yet, the majority of students in these Hawaiian schools voted these conditions as acceptable. These observations were made in both hot and cool seasons (see Kwok, 1998).

Does long-term *acclimatization* influence the sensation of thermal comfort? Researchers disagree. ASHRAE Standard 55 recognizes only two conventional comfort zones, influenced by activity and clothing. Givoni (1998) advocates

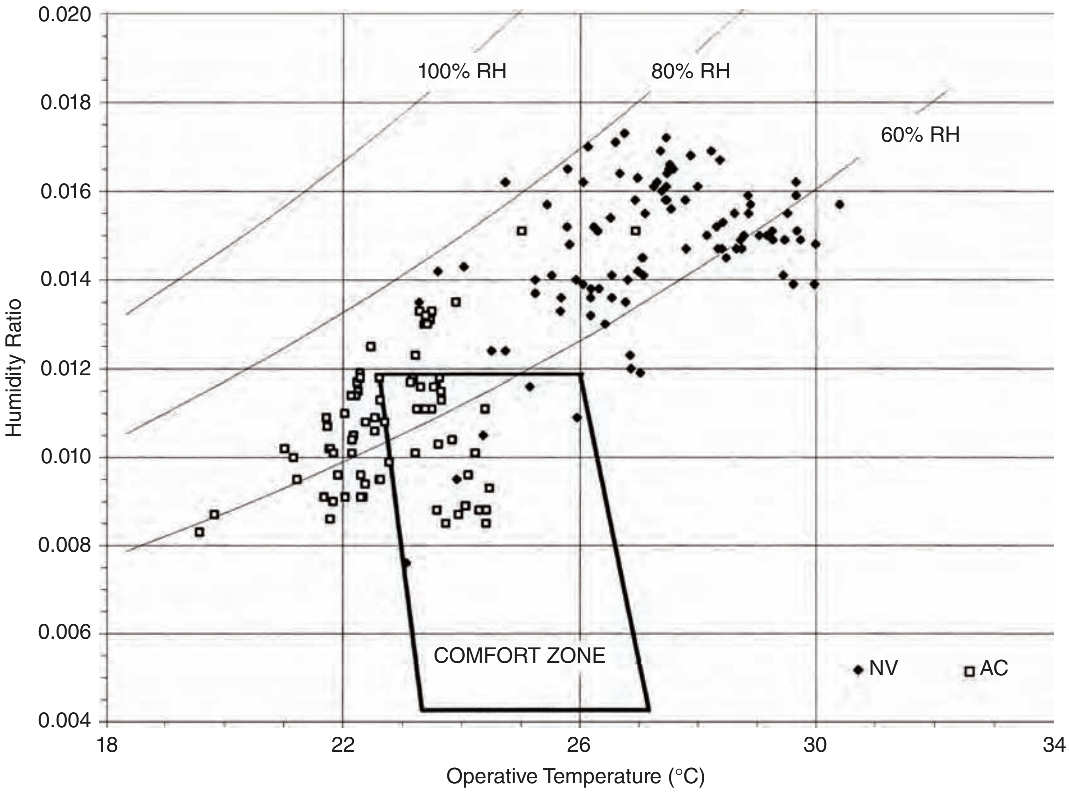


Fig. 4.13 *Natural ventilation and comfort. Measured conditions compared to the ASHRAE comfort zone (warm season) for naturally ventilated and air-conditioned classrooms in Hawaii. The majority of the occupants voted these conditions acceptable. A higher temperature and humidity comfort zone for naturally ventilated buildings is supported by studies such as this (Kwok, 1998). (Reprinted with permission of ASHRAE, from the* ASHRAE Transactions*, 1998, Vol. 104, Number 1. Note that the comfort zone has been modified to conform to ASHRAE Standard 55-2013.)*

a higher-temperature, higher-humidity limit for "hot-developing" countries (Fig. 4.14), based upon a combination of traditional and economic factors. In Fig. 4.14, an interior air speed of 2 m/s (about 400 fpm) is assumed.

An *adaptive model* of comfort recognizes acclimatization's influence as well as personal actions to influence one's own comfort. ASHRAE Standard 55 recognizes that people can be comfortable in a wide range of temperatures, and provides an optional method for determining acceptable thermal conditions for naturally ventilated spaces. Humphreys and Nicol (1998) elaborate on this approach, with occupant behaviors summarized in Table 4.5. They present a formula to determine the *indoor comfort* temperature, T_n, relative to an exponentially weighted running average of outdoor temperature, and applicable to *free-running* buildings (without mechanically—narrowly—controlled indoor temperatures):

$$T_n = 0.534\ T_{rmo} + 12.9\ (°C) \tag{4.3}$$

where T_{rmo} is in °C and represents the mean outdoor air temperature during a period of hot weather. Note that relative humidity is not included in this relationship. Using this equation, with Phoenix, Arizona's average July–August temperature of 32.3°C (90.2°F) (to approximate an exponentially weighted running average):

$$T_n = 0.534\ (32.3) + 12.9 = 17.25 + 12.9$$
$$= 30.1°C\ (86.2°F)$$

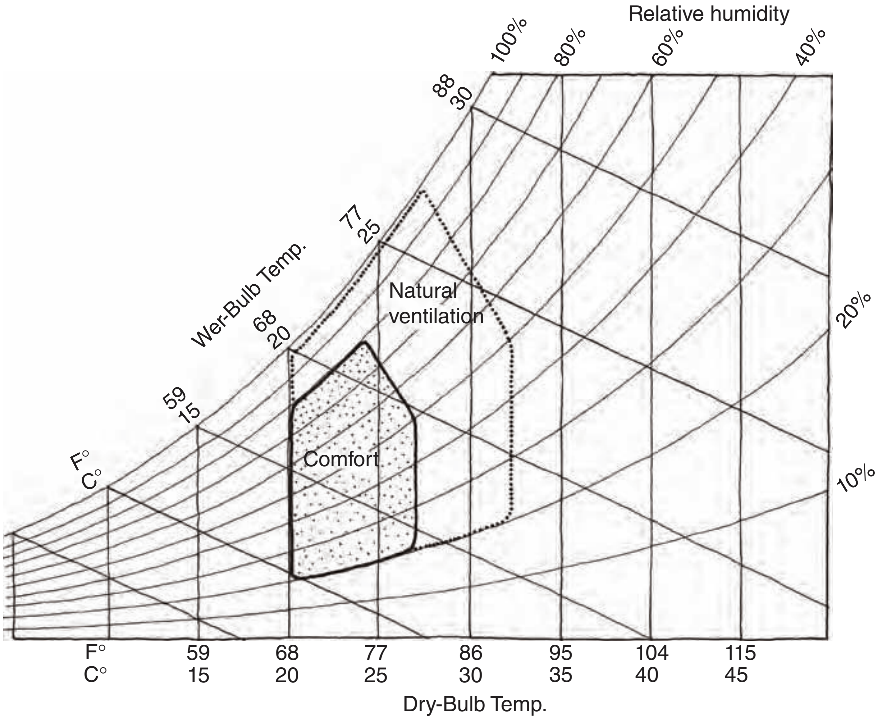


Fig. 4.14 *Suggested boundaries of outdoor air temperature and humidity within which indoor comfort can be provided by natural ventilation. Assumed air speed is 2 m/s (400 fpm). The higher limits for "hot-developing countries" assume acclimatization by those cultures. (Based upon Givoni, 1998.)*

TABLE 4.5 Adaptive Behavior for Thermal Comfort

Response Category	Actions in Response to Cold	Actions in Response to Heat
Regulating the rate of internal heat generation	Increasing muscle tension and shivering	Reducing one's level of activity Drinking cold liquids (induces sweating) Drinking hot liquids (induces sweating) Eating less Adopting the siesta routine (matching activity to the thermal environment)
Regulating the rate of body heat loss	Vasoconstriction (reduces blood flow to the surface tissues) Curling or cuddling up (reduces exposed surface area) Adding some clothing	Vasodilation (increases blood flow to the surface tissues) Adopting an open posture (increases exposed surface area) Taking off some clothing
Regulating the thermal environment	Turning up the thermostat Lighting a fire Complaining to management (so that someone else will raise the temperature) Insulating a loft or wall cavities Improving windows or doors, weather-stripping	Turning on the air conditioner Switching on a fan Opening a window Shading a window from the sun
Selecting a different thermal environment	Finding a warmer spot (such as going to bed) Visiting a friend (with a warmer place) Visiting a heated public building Building a new home Emigrating: a long-term solution	Finding a cooler spot Visiting a friend (with a cooler place) Visiting a cooled public building (or going swimming) Building a new home Emigrating: a long-term solution
Modifying the body's physiological comfort conditions	Acclimatizing, letting the body and mind become more resistant to cold stress	Acclimatizing, letting the body and mind adjust so that heat is less stressful

Source: Based on Humphreys and Nicol (1998).

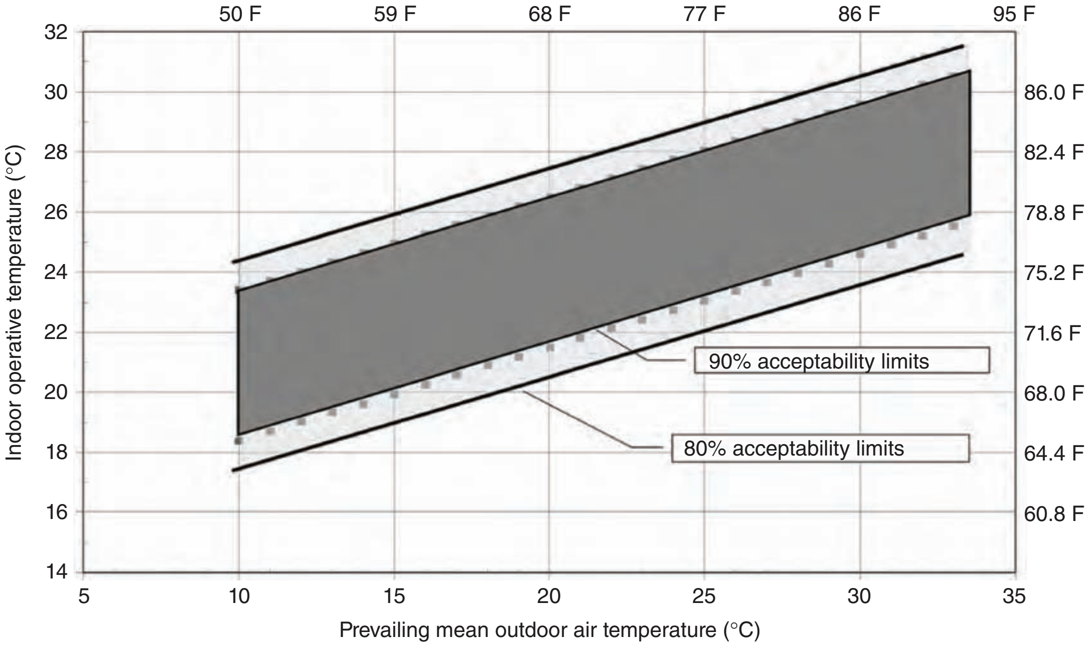


Fig. 4.15 *Acceptable operative temperature ranges for naturally ventilated spaces. (Reprinted with permission; ©ASHRAE, ANSI/ASHRAE Standard 55-2013,* Thermal Environmental Conditions for Human Occupancy.*)*

Using the adaptive method, to determine acceptable thermal conditions in naturally ventilated spaces, one can find allowable indoor operative temperatures from Fig. 4.15, which includes two sets of operative temperature ranges—for 80% and 90% acceptability limits, when the prevailing outdoor temperature is greater than 50°F (10°C) and less than 92.3°F (33.5°C). Occupants are near sedentary with metabolic rates of 1.0 to 1.3 met.

The conventional ASHRAE comfort zone (Fig. 4.5) specifies comfort zone boundaries for environments that meet specific operative temperature criteria, where the air speeds are not greater than 40 fpm (0.20 m/s), based upon specified clothing insulation values. Air speeds greater than 40 fpm (0.20 m/s) may be used to increase the upper operative temperature limit of the comfort zone in certain circumstances. For example, the borders of the warmer comfort zone (0.50 clo) may be raised 1°F for each 30 fpm (1°C for each 0.275 m/s) increase in air motion up to a limit of 82.45°F at 160 fpm (28°C at 0.8 m/s). At this air speed, loose paper, hair, and other objects might start to be blown about (however, see Table 4.6). Note: Optimum summer operative temperature is 76°F (24.4°C). For each 0.1 clo decrease in clothing, an increase of 1°F (0.6°C) is allowed in the borders of the summer comfort zone.

TABLE 4.6 Air Velocity and Comfort

Air Velocity	Possible Lower-Temperature Comfort Sensation (between 80°F and 90°F; Larger Numbers Correspond to High-Humidity Areas)	Probable Impact
Up to 50 fpm (0.25 m/s)	No change in comfort sensation	Unnoticed
50–100 fpm (0.25–0.51 m/s)	2–3F° lower (1.1–1.7C°)	Pleasant
100–200 fpm (0.51–1.02 m/s)	4–5F° lower (2.2–2.8C°)	Generally pleasant but causing a constant awareness of air movement
200–300 fpm (1.02–1.52 m/s)	5–7F° lower (2.8–3.9C°)	From slightly to annoyingly drafty
Above 300 fpm (1.52 m/s)	More than 5–7F° lower (2.8–3.9C°)	Requires corrective measures if work is to be efficient and health secured

Source: Adapted from Victor Olgyay, *Design with Climate: Bioclimatic Approach to Architectural Regionalism*, Copyright © 1963, Princeton University Press. Reprinted by permission.

The upper and lower borders for relative humidity are based upon less precise data, but in general, the lower limit seeks to avoid problems such as coughs, nosebleeds, static electricity, and dust mites from excessively dry air; the upper limit tries to keep skin wettedness within acceptable levels, as well as discourage the growth of mold and mildew.

(b) Passive Building Comfort Standards

A somewhat different approach to comfort standards has been proposed for buildings that take a passive approach to heating and cooling in areas where acceptable humidity can be maintained. In these buildings, direct sun might add significantly to body warming in winter; strong air currents might be expected to contribute to summer body cooling. These tend to be the kind of free-running buildings mentioned earlier as candidates for the adaptive model of comfort prediction.

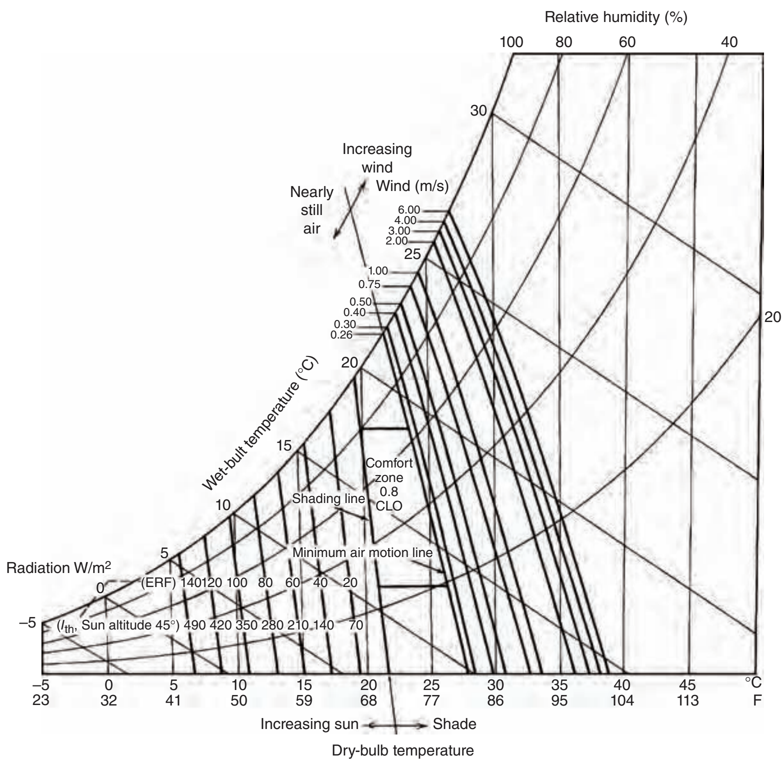
Historically, Arens et al. (1980) demonstrated a wider range of comfort conditions and considerably more tolerance for summer air motion than ASHRAE (1995). A summary of these results is shown graphically in Fig. 4.16. Such graphs are called *bioclimatic* charts because of their interrelation of climate and human comfort factors. Where the users of buildings are expected to adjust to the wider temperature swings associated with passive buildings, these guidelines may be used. Some differences in the basic assumptions of Arens et al. from those of ASHRAE (1995) should be noted:

Activity: 1.3 met (ASHRAE, 1.2 met)

Winter: 0.8 clo (ASHRAE, 1.0 clo)

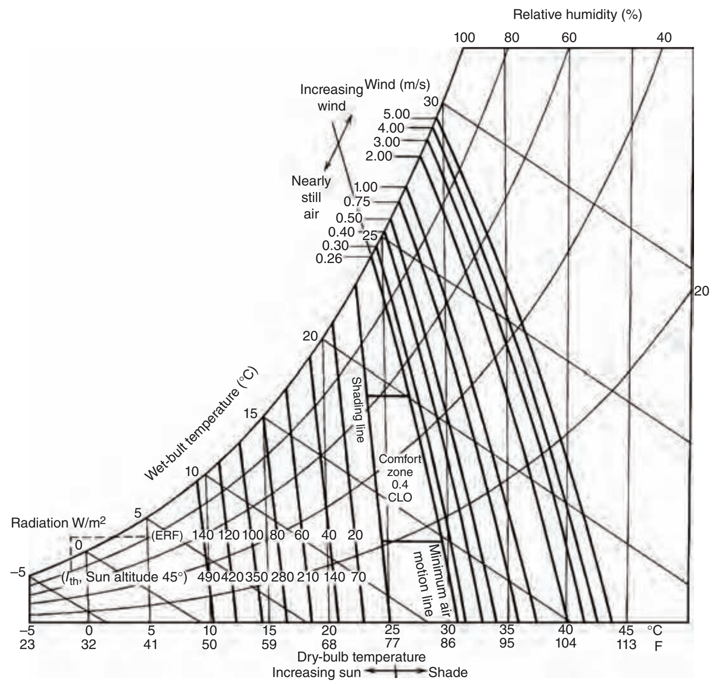
Summer: 0.4 clo (ASHRAE, 0.5 clo)

Note particularly that, rather than operative temperature, ordinary air temperature (DB temperature) is used in Fig. 4.16. Added radiant heat for conditions below the shading line can be utilized to extend the comfort zone to lower temperatures;

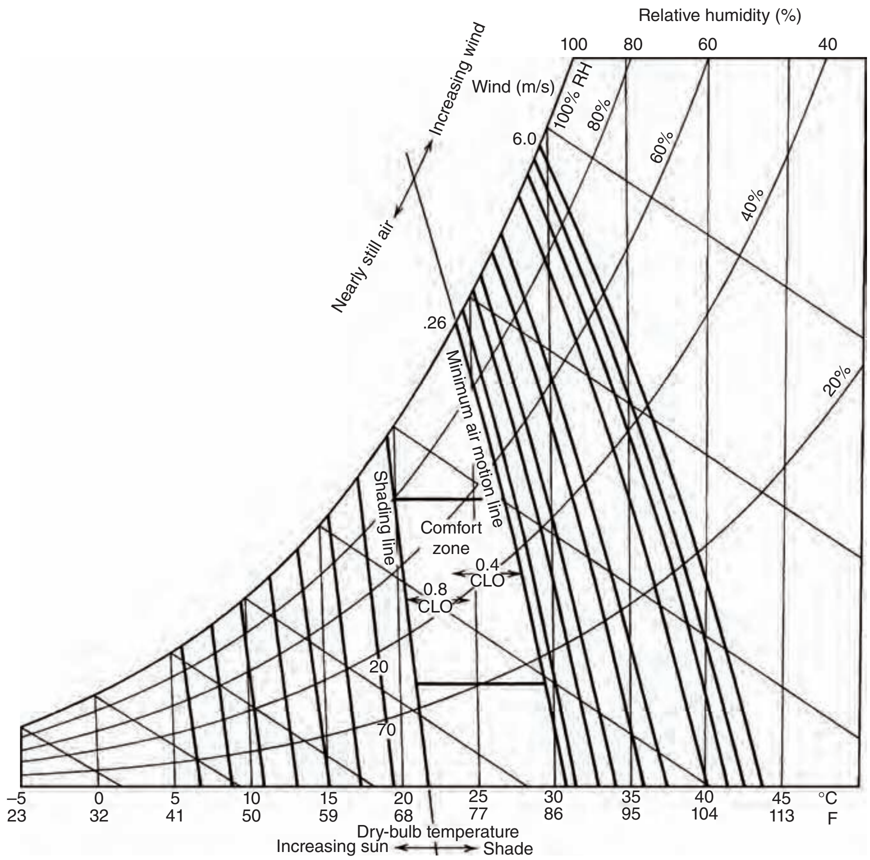


(*a*)

Fig. 4.16 *Comfort zones that encourage passively heated and cooled buildings. The "winter" (0.8 clo) comfort zone (a) and the "summer" (0.4 clo) comfort zone (b) are combined for the year-round zone shown in (c). (Based upon Arens et al., 1980.)*



(*b*)



(*c*)

Fig. 4.16 *(continued)*

added air motion above the nearly still air line can extend the comfort zone to higher temperatures. *Radiant heat* to be added to a lower-extended comfort zone is shown in Fig. 4.16 using two quantities: The effective radiant field (ERF) is a measure of the net radiant heat flux to the body from all surfaces at temperatures other than air temperature. A more convenient quantity for designers may be the total solar radiation (or *insolation*) on a horizontal surface, termed I_{th}. Insolation values are more readily available, and the added-radiation lines of Fig. 4.16 represent I_{th} converted to its approximate radiant impact on a human body's surface area when the sun is at an altitude of 45°. Arens et al. (1980) give further details on the effects of solar radiation on comfort at other sun altitudes, activity levels, and clothing combinations.

The effect of air motion on thermal comfort is shown in Fig. 4.16 for a wide range of velocities. People can easily tolerate air motion outdoors up to about 600 fpm (3 m/s), but indoor studies (Table 4.6) have indicated that about 400 fpm (2 m/s) is the maximum tolerable air speed. This limit would apply to air motion caused by overhead fans.

Caution is still advised when relative humidity is above 70% or below 20% for reasons cited earlier.

(c) Localized Comfort

How can comfort be ensured at each work station in an office or wherever people spend a lot of time? The location of heating, cooling, and ventilating components is an important detail. The human body is most affected by the thermal environment in its thermally sensitive places. Although we sweat and are sensitive to heat or cold over nearly all of our skin surface, we are most thermally sensitive in these places:

Heat receptors: fingertips, nose, elbows

Cold receptors: upper lip, nose, chin, chest, fingers

So, on a hot, humid day, cool air moving across the face is a particularly strong promise of comfort, whereas on a cold day, a burst of heat (such as radiant heat from a window, a heater, or a cup of coffee) to the face and fingers is quickly effective.

Regarding our sense of touch: Our fingertips are most sensitive to the *rate at which heat is being conducted* to colder objects or from hotter objects. The temperature of our skin at the fingertips under ordinary conditions is in the high 80s°F (high 20s°C), so our sense of touch works against many passively heated surfaces in winter, which feel cool even though they are warmer than room air temperature. These surfaces are made of materials that conduct heat rapidly so that they can soak up solar radiation without overheating the room. This high *conductivity* makes them eager to accept human warmth as well, and persuades us, as we touch them, that they are cooler than, in fact, they are. Anyone who has walked barefoot from a rug to an unheated tile floor will sense that the tile is colder, even when both have exactly the same surface temperature. This same characteristic works for passively cooled surfaces in summer.

Unwanted local cooling of the body is called a *draft*. It is a particularly serious threat in winter, yet summer drafts from very cool conditioned air are also bothersome. Figure 4.17 shows the percentage of people dissatisfied due to a perceptible draft on their head, neck, shoulders, and back. Again, this applies to sedentary people wearing normal indoor clothing. Draft sensation depends on air speed, activity, and clothing. Many air-conditioning systems deliver summer supply air at temperatures as low as 55°F (13°C), well below the lowest temperature shown here. The standard warmer season 50 fpm (0.25 m/s) air speed at such supply air temperatures seems to threaten more than 40% dissatisfaction from drafts. However, ceiling fans with the same air speed, for comfort at higher temperatures

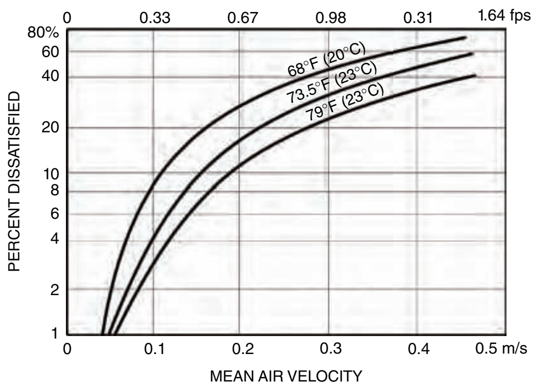


Fig. 4.17 *Percentage of people dissatisfied as a function of mean air velocity. Note the influence of air temperature: The lower the temperature, the higher the dissatisfaction. (Reprinted with permission; ©ASHRAE, 2013* ASHRAE Handbook—Fundamentals.*)*

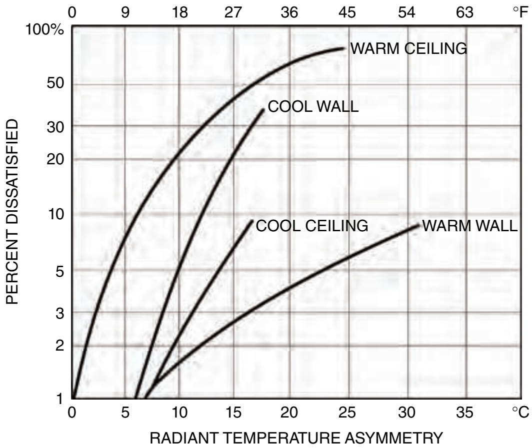


Fig. 4.18 *Percentage of people expressing discomfort due to radiant asymmetry. A warmer ceiling produces the highest discomfort; a warmer wall, the least discomfort. (Reprinted with permission; ©ASHRAE, 2013* ASHRAE Handbook—Fundamentals.*)*

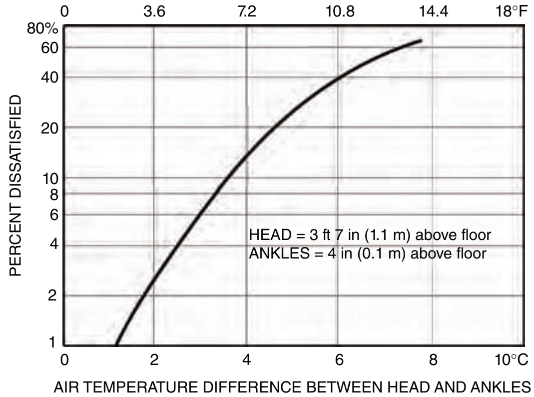


Fig. 4.19 *Percentage of people dissatisfied as a function of the vertical air temperature difference between the head (higher temperature) and ankles (lower temperature). A cold floor proved uncomfortable. (Reprinted with permission; ©ASHRAE, 2013* ASHRAE Handbook—Fundamentals.*)*

such as 80°F (27°C), should cause less than 15% dissatisfaction.

Another comfort factor is *radiant asymmetry*, the difference between the temperatures of two opposite surfaces as experienced by a body seated between them, when one of these surfaces is markedly different in temperature from all other surfaces within a space. Figure 4.18 shows that more dissatisfaction arises from warm ceilings (typical of radiantly heated ceilings in winter) than is caused by hot and cold wall surfaces. Less serious were "cool walls" (typical of a cold window in winter). Less than 10% dissatisfaction resulted from "cool ceilings" (such as radiant cooling panels in summer) and even less from "warm walls" (typical of a sunny window in summer or a passively heated mass wall in winter).

Because warm air is less dense than cold air, it rises; therefore, in most building spaces, air temperature is somewhat higher at the ceiling than at the floor, regardless of the season. Figure 4.19 shows experimental results of dissatisfaction with a vertical air temperature difference between the head at 43 in. (1.1 m) and the feet at 4 in. (0.1 m). (When the head level was cooler than the floor, much greater temperature differences were tolerated.) Air temperature difference between head level and ankle level should not exceed 5.4°F (3°C).

(d) Evaluating Comfort

Designing comfortable conditions that maintain the environment within the range specified by these standards is a complex combination of assembling mechanical systems, control systems, and building enclosures. Understanding the physical interactions that occupants might experience within a space has become easier to calculate (and visualize) with the Web-based interface Thermal Comfort Tool for evaluating comfort according to ASHRAE Standard-55, developed by the Center for the Built Environment (CBE) and the University of California, Berkeley (Fig. 4.20). The tool offers designers evaluation of comfort in conventional building systems using the predictive mean vote (PMV) model, in natural ventilation systems (adaptive comfort model), and in buildings with ceiling or desk fans. Thermal comfort calculations can be exported into a format that is ready to support LEED documentation for USGBC certification.

(e) Passive House Comfort

The origins of the Passive House standard began with passive solar design and superinsulation techniques during the 1970s in the United States and Canada. In the 1990s European scientists refined these concepts and design techniques to develop

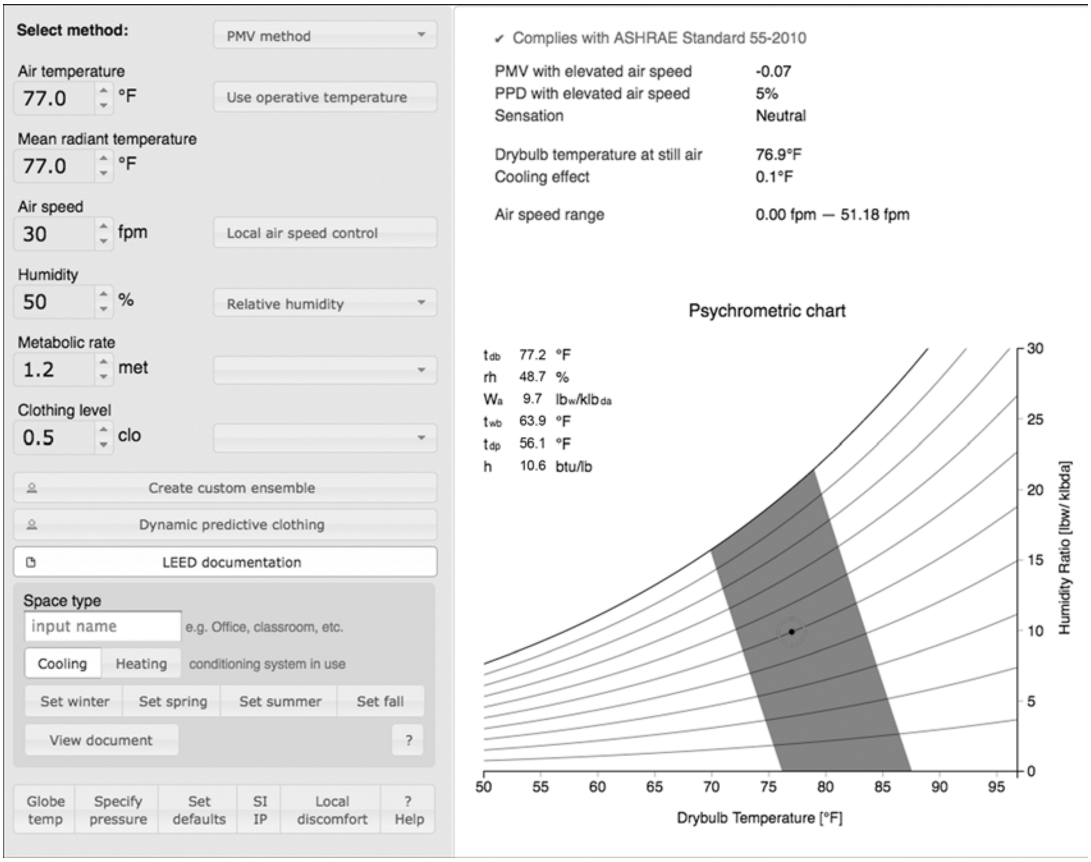


Fig. 4.20 *CBE Thermal Comfort Tool. Left side shows user input fields. Top-right section contains the results of the calculations. Bottom-right section contains a visualization of thermal comfort conditions as a psychrometric chart, temperature-humidity chart, or the adaptive comfort chart. (Hoyt Tyler, Schiavon Stefano, Piccioli Alberto, 2013, CBE Thermal Comfort Tool for ASHRAE-55. Center for the Built Environment, University of California Berkeley, http://cbe.berkeley.edu/comforttool/; used with permission.)*

the Passive House standard tailored to the Central European climate zone.

As both an energy standard and set of design and construction principles, the Passive House concept promises superior comfort and an overall reduction of 65–75% total energy use compared with conventional buildings. The design approach is a well-insulated, airtight building that is heated by solar gains, people, equipment, and lighting; heat losses are minimized by thermal-bridge-free construction and well-insulated, airtight envelopes.

A number of strategies help to increase thermal comfort and reduce energy use in buildings built to the Passive House standard. Even though all the guiding principles must work in concert, the first three principles are critical in the schematic design phase of a project. As the design progresses, thermal bridging and airtightness can be tested and the design optimized through WUFI-Passive energy modeling and planning software. The principles are:

1. ***Compact building shape.*** Design for compact building shapes, as opposed to long and narrow forms, for low surface-to-volume ratios (< 1) (generally holds true for mild climates).
2. ***Optimal solar orientation and shading.*** Maximize solar gains for winter through transparent openings, and minimize summer solar gains with shading.
3. ***Continuous insulation.*** Create steady indoor temperatures that will not go below 42°F (5.6°C) in very cold U.S. climates (50°F [10°C] in central European climates) in the absence of a heating system by designing highly insulative

envelopes and using window assemblies with thermal breaks.

4. ***Thermal-bridge-free construction.*** Minimize any transfer of heat and moisture through the envelope to prevent energy loss, condensation, or building deterioration. The effectiveness of construction details may be checked using THERM (a free program provided by the Lawrence Berkeley National Laboratory that analyzes two-dimensional heat transfer through building assemblies).
5. ***Airtightness.*** Minimize air infiltration into/through wall assemblies.
6. ***Balanced ventilation with heat recovery.*** Specify a heat recovery ventilator or energy recovery ventilator to provide exceptional efficiency, indoor air quality, and thermal comfort.
7. ***Energy-efficient appliances and lighting.*** Specify highly efficient appliances and lighting to minimize overall energy use.
8. ***User manual.*** Develop a user-friendly building operations manual to give to the owner.

The comfort criteria in Passive House building construction:

- The air velocity in the occupied zone must be less than 19.7 fpm (0.1 m/s). This criterion limits both the air permeability of a component as well as potential draftiness.
- Average room temperature compared to the average wall surface temperature should not differ by more than 7.56°F (4.2°C).

References and Resources

Arens, E., R. Gonzalez, L. Berglund, P. McNall, and L. Zeren. 1980. "A New Bioclimatic Chart for Passive Solar Design," *Proceedings of the Fifth National Passive Solar Conference*, vol. 5.2, pp. 1202–1206. American Section of the International Solar Energy Society. Boulder, CO.

ASHRAE. 2013. *ASHRAE Handbook—Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, GA.

ASHRAE. 2013. ANSI/ASHRAE Standard 55-2013, *Thermal Environmental Conditions for Human Occupancy.* American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, GA.

Egan, M. D. 1975. *Concepts in Thermal Comfort*. Prentice-Hall. Englewood Cliffs, NJ.

Givoni, B. 1998. *Climate Considerations in Building and Urban Design*. Van Nostrand Reinhold. New York.

Givoni, B. and M. Milne. 1979. "*Architectural Design Based on Climate*," in *Energy Conservation in Building Design*, Donald Watson (ed.). McGraw-Hill, Inc. New York.

Heschong, L. 1979. *Thermal Delight in Architecture*. The MIT Press. Cambridge, MA.

Hoyt, Tyler, Stefano Schiavon, Alberto Piccioli, Dustin Moon, and Kyle Steinfeld. 2012. CBE Thermal Comfort Tool for ASHRAE-55. Center for the Built Environment, University of California Berkeley, http://cbe.berkeley.edu/comforttool/

Humphreys, M. and J. F. Nicol. 1998. "Understanding the Adaptive Approach to Thermal Comfort," *ASHRAE Transactions*, vol. 104, no. 1.

Kwok, A. 1998. "Thermal Comfort in Tropical Classrooms," *ASHRAE Transactions*, vol. 104, no. 1.

Passivhaus Institut. http://passiv.de/

Passive House Alliance United States (PHAUS). http://www.phaus.org/

Passive House Institute United States (PHIUS). http://www.passivehouse.us/

CHAPTER 5

Indoor Air Quality

SINCE THE ADVENT OF MODERN HVAC SYSTEMS, ventilation has generally been addressed via heating and cooling system design efforts. In centuries past, however, there were special systems to provide outdoor air to buildings, even at the residential scale. Banham (1969) describes both large and small buildings where outside air was deliberately introduced. In the home that Dr. John Hayward built for his family in 1867, the Octagon in Liverpool, England (Fig. 5.1), outdoor air was brought into the basement, slowed down to precipitate some particulates, then heated to help it rise throughout the four-story building. Ceiling vents just above gas lights drew "vitiated" air from each room, which was then vented to a "foul air chamber" in the attic. From there, a large shaft functioned using a combined siphon and stack effect. Powered at its low point by ever-present heat from the kitchen cooking range, it drew the foul air down, then up a very high chimney to discharge.

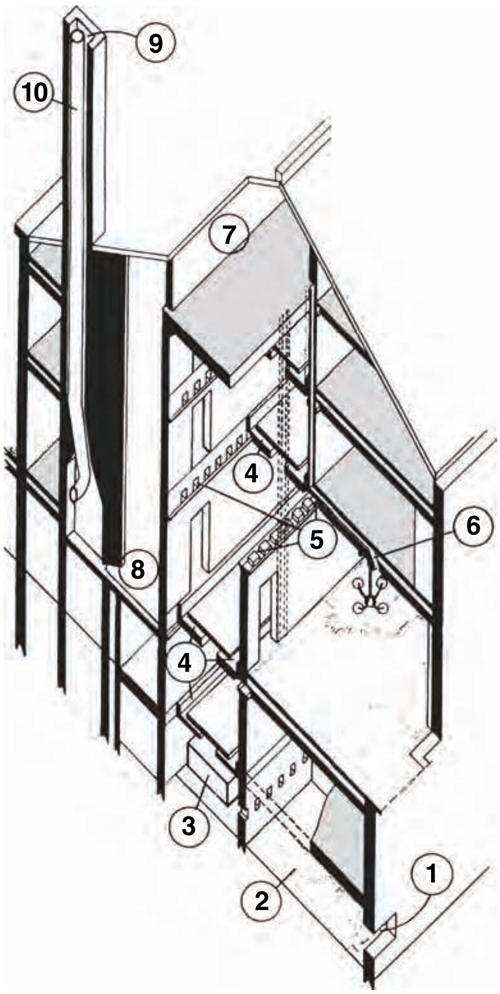


Fig. 5.1 *Fresh air intake, stale air exhaust at the Octagon, Grove Street, Liverpool, England, 1867. Dr. John Hayward built this exhaust system. Dirty air outside (coal-fired industries and buildings were common) and inside (gas lamps) probably produced an IAQ considerably worse than today's norms. 1. Fresh air intake; 2. Settling chamber in the basement; 3. Heating coils; 4. Air passages in lobby floors; 5. Air passages in the cornice; 6. Extract above a gas lamp; 7. Foul air chamber; 8. Foul air down a duct; 9. Foul air chimney; 10. Flue from a kitchen range. (Reprinted by permission from Reyner Banham. 1969.* The Architecture of the Well-Tempered Environment*. The Architectural Press. London.)*

5.1 INDOOR AIR QUALITY AND BUILDING DESIGN

Several trends have combined to bring indoor air quality (IAQ) concerns back into prominence. First, an increasingly large percentage of people's time is now spent indoors, and in more tightly controlled environments, as a service-based economy overtakes a manufacturing-based one. Second, the oil embargo of 1973 raised the world's awareness of finite energy sources, producing a sudden and powerful rush toward energy-conserving designs. This, in turn, encouraged designers to limit the introduction of outdoor air that required cooling in summer and heating in winter. Third, a proliferation of chemicals in our environment has produced a vast array of potential air pollutants—from synthetic products permanently installed in buildings, from equipment used indoors, and from cleaning fluids used in maintenance. With more time spent in stale air and surrounded by more pollution sources, increasing numbers of businesses have reported cases of *sick building syndrome* (SBS). SBS (by one definition) is a situation wherein more than 20% of the occupants complain of symptoms associated with SBS—such as headaches, upper respiratory irritation, and irritation of the eyes, among others. If these symptoms disappear after occupants leave the workplace (weekends are especially good periods of contrast), SBS is strongly indicated.

The building designer has an elusive task when air quality is an issue, because so little can be accurately predicted. Heat flow rates, occupancy schedules, and typical weather patterns can be combined to estimate with some confidence how much energy will be consumed by a building; construction types can then be altered in the design stage to yield predictably different results. But designers have few tables that provide rates of outgassing for various materials at given temperatures and no well-established data on design conditions for the quality of local or (regional) outdoor air, even though there is readily available and reliable information for air temperature and humidity.

Controlling the quality of indoor air may be as important to building occupants as controlling for thermal or acoustical comfort. Designers know that saving energy for heating and cooling lowers the cost of maintaining a building; employers know that lost productivity from on-the-job illness or sick leave can result in much greater costs. One estimate for a large office building compared the cost of increasing ventilation and improving air filtration to the value of projected health and productivity benefits. Initial improvements yielded estimated benefit-to-cost ratios of 50 to 1 (increased ventilation) and 20 to 1 (improved filtration). Acceptable thermal conditions and acceptable IAQ are *not* synonymous. Buildings that are thermally comfortable can still cause SBS when pollutants are sufficiently numerous.

ASHRAE (Standard 62.1, 2013) has defined acceptable indoor air quality as: "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction." There are two components to this definition—a comfort response and a health benchmark. Providing acceptable IAQ depends upon four major considerations, three of which depend largely on the designer:

1. Limiting pollution at the source (choosing materials and equipment carefully)
2. Isolating unavoidable sources of pollution
3. Providing for an adequate supply and filtering of fresh air (and recirculated air)
4. Maintaining a building and its equipment in a clean condition

Dealing with indoor pollution at its source, by choosing materials and equipment with care, rather than increasing outdoor airflow rates (and related energy consumption) is the most rational IAQ strategy. The designer can further provide for improved IAQ by carefully locating a building on its site; zoning to isolate pollutant sources; and providing clean, adequate, and well-distributed outdoor air, air-cleaning devices, and building commissioning. Providing a *flush mode* following completion of construction might be considered. It is up to a building's managers to maintain IAQ by means of a regular equipment maintenance program, regular interior cleaning, and a careful selection of cleaning agents. Furthermore, a flush of the building after every unoccupied weekend or holiday period is helpful in removing pollutants accumulated from finishes and furnishings.

While many factors determine acceptable indoor air quality, ASHRAE Standard 62.1 (2013) provides minimum ventilation rates for the occupied breathing zones. These rates are based on the occupancy category (e.g., school, restaurant, hotel, office) and the number of people, in cubic feet per minute (liters per second) per person. Other tables include minimum exhaust rates and maintenance activities, for inspection, cleaning, maintaining, and verifying such items as dampers, actuators, humidifiers, sensors, drain pans, and cooling towers.

Carbon dioxide levels can serve as a proxy for ventilation effectiveness, where the balance of oxygen consumed and the carbon dioxide generated depends on the level of physical activity in a space. The informative appendix of ASHRAE Standard 62 offers the guidance that spaces should maintain concentrations of CO_2 no greater than approximately 700 ppm above the outdoor air levels (whereby a substantial number of visitors will be satisfied with odors). Carbon dioxide concentrations in outdoor air typically range from 300 to 500 ppm.

5.2 POLLUTANT SOURCES AND IMPACTS

Indoor air pollution can be described both in terms of the types of contaminants (gaseous, organic, or particulate) and the types of effects (odors, irritants, toxic substances) involved. People not only inhale contaminants, but also absorb and ingest some—the nose is not the only pollutant receptor/sensor. Table 5.1 summarizes some common indoor air pollutants, their effects, and simple strategies to ameliorate them. For some contaminants, the only method of avoidance is to design for their exclusion; equipment will not remove them, although increased ventilation can reduce their impact. Examples are asbestos, radon, and pesticides.

(a) Odors

One of the most immediate indicators of IAQ problems is odor. People are sensitive to odors over an extraordinary range, whereas equipment to detect and classify odors is woefully lacking. Odors are perceived most strongly on initial encounter; then "fatigue" occurs and perception fades. Thus, visitors are more likely to detect odors than are the long-term inhabitants of a space. Odors may be simply unpleasant, with psychological consequences, or may be indicators of a more serious IAQ problem with physiological consequences. When an unfamiliar odor is detected, our reactions are positive, neutral, or negative, depending upon whether we perceive a threat (or enjoyment) from the odor.

Sometimes odors are directly traceable to a source, but in office environments odors are usually more complex. A typical office environment odor blend may include contributions from body odors, grooming products (perfumes, colognes), copy machines, food products, cleaning fluids, and outgassing from materials. More rarely, in a decreasing number of locales, tobacco smoke may also be present. This complexity produces an interesting reaction; people tend to become less sensitive to each of the component odors, with a resulting overall masking. However, an architecturally imposed masking approach—the deliberate introduction of a "perfume" to cover offending odors—is rarely successful. (Sweet-and-sour may work nicely for the palate, but olfactorily it can be uniquely nauseating.) Conversely, as the indoor environment is cleansed of multiple odors, people become more sensitive to the one or two odors that remain.

Often a simple measurement of carbon dioxide (CO_2) concentration is used as a first indicator (a surrogate) of potential IAQ problems related to occupancy, because the CO_2 concentration indoors is generally proportional to the concentration of individuals.

Filtering odors from indoor air is usually accomplished with electronic or activated charcoal filters, described in Section 5.6.

(b) Irritants

Unlike odors, which are immediately perceived and fade with prolonged exposure, irritants are often imperceptible at first but cause increasing distress over time. Symptoms of irritants include itching or burning eyes, sneezing, coughing, dry nose and throat, sore throat, and tightness of the chest. Most irritants are present in the form of particles and gas dispersoids (Table 5.2).

Sources of irritants typically include the building itself and the equipment and occupants within. New and newly renovated buildings are particularly prone to problems from outgassing of paints, adhesives, sealants, office furniture, carpeting, and vinyl wall coverings. *Volatile organic compounds* (VOCs) are chemicals containing carbon molecules that are volatile; that is, they off-gas or evaporate from material surfaces at room temperatures. The VOC list is long: methane, ethane, methylene chloride, trichloroethane, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons

TABLE 5.1 Common Air Pollutants

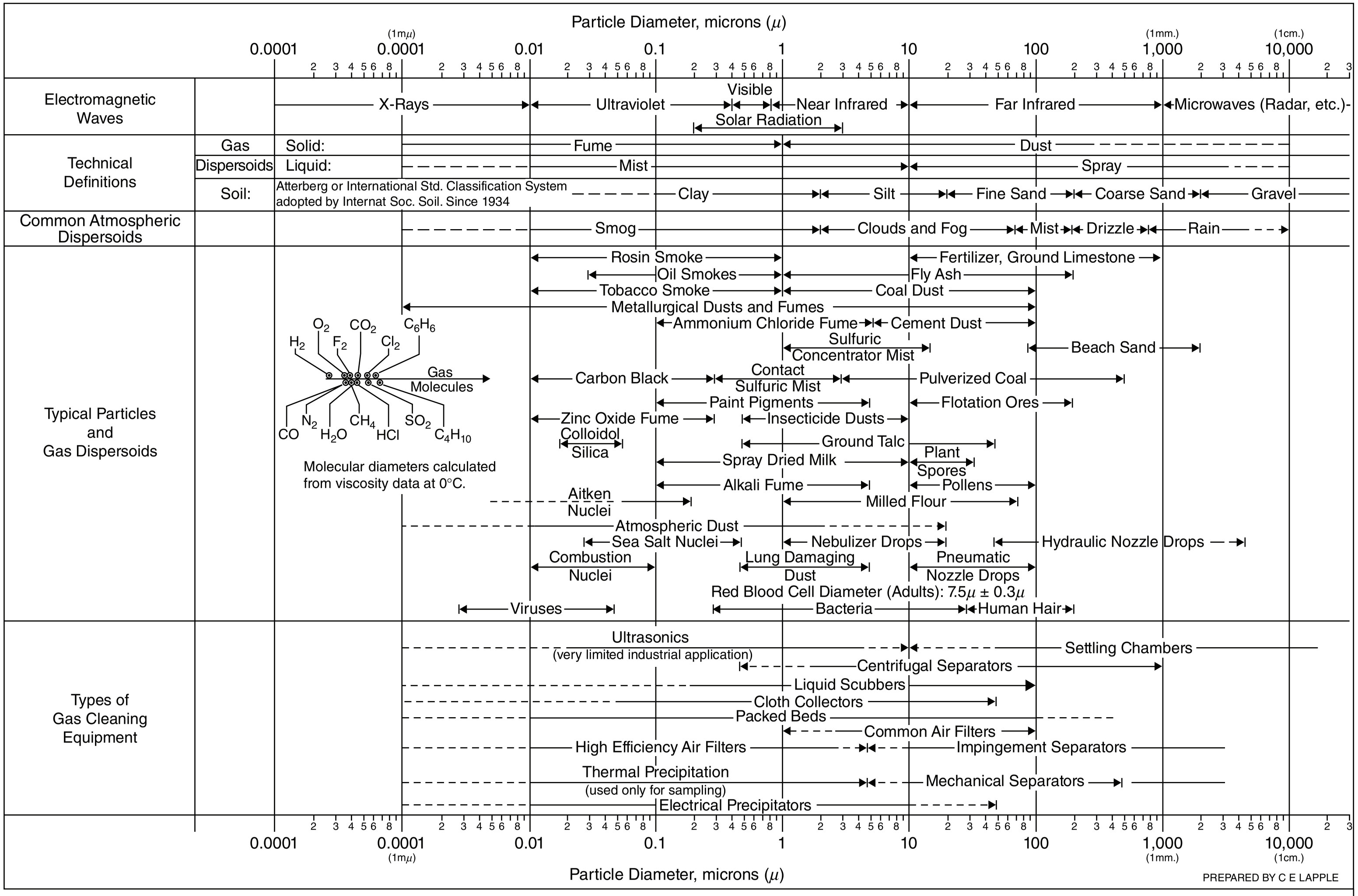
Pollutant	Sources	Effects	Control Strategies
Excess moisture[a]	Cooking (heating open liquids), washing, exhaling	Increases growth of fungi, bacteria, and dust mites	Exhaust ventilation at source; dehumidification
Carbon dioxide (CO_2)	Human respiration	Minor discomfort at high concentrations; "stuffiness"	CO_2 is a good indicator of the ventilation rate in tightly enclosed spaces or where occupancy is high
Carbon monoxide (CO)	Incomplete combustion: furnaces, stoves, fireplaces; motor vehicle exhaust	Headaches, dizziness, sleepiness, muscle weakness, potentially lethal	Sealed combustion burners, adequate combustion air, safe exhaust flues
Nitrogen oxides	High-temperature combustion	Irritation, possible immune suppression	Safe exhaust flues, sealed combustion burners
Sulfur oxides	Combustion fuels containing sulfur (oil, coal)	Potential irritant, burning eyes, reduces lung function	Alternative fuels, safe exhaust flues, sealed combustion burners
Polynuclear aromatic hydrocarbons	Smoking, combustion of wood or coal, barbecuing, burnt food	Irritants and carcinogens	Prohibit smoking, lower temperature in cooking, use clean fuels, burn wood in enclosed firebox with adequate oxygen supply
Ozone	Laser printers, photocopiers, small motors, electronic air cleaners	Inflammation of bronchia, wheezing and shortness of breath, dizziness, asthma attacks	Remove sources or exhaust at source, maintain electronic air cleaners
Volatile organic compounds (VOCs) Formaldehyde	Particle board, interior laminated panels, glues, fabric treatments, paints	Burning eyes and nose, skin rash, shortness of breath, headaches, nausea, dizziness, fatigue	Use alternative materials, seal particle board if used, ventilate
Others	Paints, solvents, carpets, soft plastics, adhesives, caulkings, softwoods, paper products, cleaning and maintenance products	Intoxication, burning eyes and nose, shortness of breath, headaches, nausea, dizziness, loss of judgment, panic	Use alternative materials, age materials before installing, ventilate
Lead	Pre-1970s paint, pre-1985 pipes and solder, dust and soil near roads (residue from leaded gas)	Neurotoxic, especially if ingested by young children; learning disabilities, nausea, trembling, numbness of extremities	Identify and remove or seal old paint, replace pipes and solder, avoid foods grown by roadside
Pesticide residues[b]	Treated basements and foundations, treated ceiling and wall cavities, treated cabinets and closets, treated soil outside foundation	Neurotoxic or long-term risk of liver, kidney, and other diseases, including cancers	Identification and removal by expert if history known, sealing in pesticide if possible
Asbestos fiber	Pre-1975 steam pipe and duct insulation, furnace and furnace parts, pre-1980 reinforced vinyl floor tile, and fiber cement shingles and siding	Long-term cancer risk from inhaling fibers	Leave material undisturbed, get expert identification and removal if required, seal with special sealant and cover with sheet metal if not crumbling
Mineral and glass fiber	Thermal insulation, pipe insulation, fire-resistant acoustic tile and fabrics	Potential irritant, burning eyes, itching skin, long-term risk of lung damage and cancer	Handle only with respirator and gloves, seal and enclose, do not disturb in place
Fungus particles, dust mites	Grow in basements, damp carpet, bedding, fabrics, walls and ceilings, closets	Very allergenic, burning eyes and nose, sneezing, skin rash, congestion, and shortness of breath	Keep surfaces dry and clean, cover bedding and upholstery with barrier cloth, ventilate, use borax treatments to retard fungus
Hazardous bacteria (e.g., Legionella)	Standing warm water, untreated hot tubs, air-conditioning drain pans, humidifier reservoirs	Severe respiratory illness, potentially lethal	Prevent standing water, clean and treat tubs and reservoirs
Radon gas	Natural radioactivity in soils	Increased lifetime lung cancer risk	Seal foundation and floor drains, ventilate subsoil
Methane and other soil gases	Decomposing garbage in landfills, leaking sewage lines, toxic waste	Possibly explosive or toxic, nuisance odors	Know site history before building, remove soil if necessary, seal foundation and floor drains, ventilate subsoil

Source: Adapted from Rousseau and Wasley (1997).

[a]Too little moisture also adversely affects health.

[b]Pre-1980s treatments are more likely to leave residues and be toxic.

TABLE 5.2 Characteristics of Particles and Particle Dispersoids



Source: Reprinted with permission of SRI International (formerly the Stanford Research Institute), Menlo Park, CA.

(HFCs), formaldehyde, and hydrocarbons such as styrene, benzene, and alcohols. All are now found frequently in new buildings.

Long-term occupancy brings other irritants. Ozone, valuable in the upper atmosphere but a smog component below, is produced by copy machines, high-voltage electrical equipment, and—ironically—electrostatic air cleaners. Mineral fibrous particles can be produced by the breakdown of duct liner/insulation and fireproofing. Hydrocarbon compounds come from copy machines and copy papers. Tobacco smoke is a mixture of gases and fine particles that can be especially irritating to many individuals. Low humidity can exacerbate problems with irritants, producing symptoms similar to those from chemicals. Carpet shampooing yields organic solvents and ammonia; nighttime cleaning coinciding with reduced or nonexistent ventilation is especially problematic. In contrast, night maintenance with *increased* ventilation rates—as with cooling by night ventilation of thermal mass—can reduce this threat.

As with odors, the impacts of irritants can be reduced with an increased outdoor air supply. Filters for the removal of irritants usually consist of particulate filters; less common are gaseous-removal filters, air washers, and electronic air cleaners.

(c) Toxic Particulate Substances

At the top of this list is asbestos, widely used in buildings until its toxicity was realized in the 1970s. Asbestos in tightly bound form is encountered as asbestos-cement and in vinyl-asbestos floor tiles; its loosely bound form is sprayed-on asbestos insulation. The latter is particularly dangerous, readily releasing toxic asbestos fibers over the life of the material. With asbestos, neither increased ventilation nor filtering is acceptable; it must be either removed under stringent isolation controls or sealed and left in place.

Some of the respirable particles (see Table 5.2) that result from incomplete combustion are toxic. Incomplete combustion can occur from tobacco smoking, in woodstoves, fireplaces, and gas ranges, and from unvented gas or kerosene space heaters. Lacking control of combustion at its source, the remedies are to isolate the source insofar as possible, exhaust air from the immediate vicinity, increase the outdoor air supply to the area, and utilize particle filtering.

(d) Biological Contaminants

Because living things inhabit both buildings and outdoor air, there will be biological contaminants such as bacteria, fungi, viruses, algae, insect parts, and dust within buildings. Moisture encourages both the retention and growth of these contaminants; standing water (which may occur in HVAC system components) and moist interior surfaces are likely trouble sites. Allergic reactions and infectious and noninfectious diseases can result. Outbreaks of Legionnaire's disease have occurred when improperly maintained HVAC systems incubated and then distributed disease-causing microorganisms. Now residential humidifiers, dehumidifiers, and air-conditioner drain pans are suspect.

Remedies for biological contaminants begin with good design and end with vigilant maintenance. Although exposure to ultraviolet radiation is sometimes used as a control strategy, filters are rarely an effective solution for these contaminants.

(e) Radon and Soil Gases

Radon is a radioactive gas that decays rapidly, releasing radiation at each stage. It is colorless and odorless, and thus undetectable by human senses. If we inhale radon, radiation release in the lungs can cause lung cancer. Other soil gases include methane (usually odiferous) and some pesticides that can volatize and enter buildings with soil gases. Effects on human beings are not likely to be beneficial.

In many buildings with high levels of radon, the problem has been traced to exposure to soil. Radon penetrates through floor and wall cracks and openings around plumbing pipes; thus, below-ground spaces are particularly at risk. Penetrations of below-grade walls and floors should be both minimized and well-sealed; under-slab ventilation (Section 5.5*c*) may be appropriate, especially in areas of high radon risk.

5.3 PREDICTING INDOOR AIR QUALITY

Assuming that pollutant sources have been minimized, designers essentially need to know how much outdoor air and what extent of filtering will produce acceptable indoor air quality. These questions are difficult to answer.

(a) Ventilation Rate

The most common remedy for SBS (after controlling pollution sources) is to increase the rate of outdoor air ventilation. Recommended rates of ventilation are found in Tables F.1 (nonresidential) and F.2 (residential). Although very small amounts of outdoor air will provide sufficient oxygen, and although human body odor control is usually achievable at a rate of 6 to 9 cfm (cubic feet per minute) (3 to 4.5 L/s) of outdoor air per occupant, outdoor air has to do more than provide oxygen and control odors. Defining minimum outdoor air supply rates has proven to be a controversial task. The current ASHRAE ventilation standard (Standard 62.1-2013—for other than low-rise residential buildings) establishes minimum rates (Table F.1) on the basis of an occupancy component and a building component, in recognition of these distinct contaminant sources. Some feel that the outdoor air requirements are too high, others that they are too low.

Two units of measurement have been proposed to integrate the various indoor air pollutants in the same way that they are perceived by human beings. The *olf* is a unit of pollution (1 olf = the bioeffluents produced by the average person); the *decipol* is a unit of perceived air quality. These are related in this proposed comfort formula:

$$Q = 10\frac{G}{C_i - C_o}$$

where

Q = ventilation rate, L/s
G = total pollution sources, olf
C_i = perceived indoor air quality, decipol
C_o = perceived outdoor air quality, decipol

At present, C_i is recommended to be set at 1.4 decipol, which represents an expectation that 80% of occupants will be satisfied with IAQ. C_o and G may be roughly estimated from Table 5.3. This approach is discussed in more detail in Fanger (1989).

The concept of *replacance* affects the design of ventilation systems. Table 5.4 shows that at the rate of 1 air change per hour (ACH) of outdoor air, an indoor space would have only 63% "new" air after 1 hour; about 8 hours at this rate is required for all the "old" air to be exhausted. There is, then, a difference between the fresh air input rate (ACH) and the replacance—the fraction of air molecules at one specified time that was *not* in the indoor space at an earlier reference time. This relationship, along with details of air pollutants (and of heat exchanger design for energy conservation), is thoroughly discussed in Shurcliff (1981).

TABLE 5.3 Estimating Indoor Air Quality

PART A. **PERCEIVED OUTDOOR AIR QUALITY, C_o**	
During smog episodes	>1 decipol
In cities with moderate air pollution	0.05–0.3 decipol
On mountains or at sea	0.01 decipol

PART B. **ESTIMATED OLF LOADS IN OFFICES PER m² of FLOOR AREA**	
Pollution Source	**olf/m²**
Occupants (10 m² per person)	
Bioeffluents	0.1
Additional load from 20% smokers	0.1
40%	0.2
60%	0.3
Materials and ventilation system	
Average in existing buildings[a]	0.4
Low-olf buildings[b]	0.1
Total load in office buildings	
Average in existing buildings (40% smokers)	0.7
Low-olf buildings (nonsmoking)	0.2

Source: Fanger (1989). "The New Comfort Equation for Indoor Air Quality." Reprinted by permission of ASHRAE, from the ASHRAE Journal, October 1989.

[a]Based upon field studies of 15 randomly selected buildings in Copenhagen.

[b]Designed to contain low-outgassing materials and a frequently maintained ventilating system.

The campus for the Environmental Protection Agency (EPA) in Research Triangle Park, North Carolina, was designed with special emphasis on IAQ (Fig. 5.2). The designers considered several alternatives for fresh air provision, deciding that a simple variable air volume (VAV) system, set at a minimum of 3 ACH (of combined fresh and recycled air) would be acceptable. If the system had been designed with a typical minimum, only 1 ACH would have resulted during periods when neither heating nor cooling was required (typical spring and fall conditions). A 6 ACH alternative would have dramatically increased energy consumption.

(b) Testing

When a client is especially interested in IAQ, full-scale time tests can be used. At the EPA campus (Fig. 5.2), the contractor was given a target for allowable contaminant concentrations (Table 5.5, Part B). Any

TABLE 5.4 Air Replacance Compared to Input Air Changes per Hour (ACH)

Note: Mixing is considered continuous and vigorous—as would be obtained in a forced-ventilation system.

Time from Start of Run (h)	Rate of Air Input (ACH):	*Replacance* (%)								
		0.06	0.12	0.25	0.5	1	2	4	8	16
1/16		0.4	0.8	1.6	3.1	6.1	11.7	22.1	39.3	63.2
1/8		0.8	1.6	3.1	6.1	11.7	22.1	39.3	63.2	86.5
1/4		1.6	3.1	6.1	11.7	22.1	39.3	63.2	86.5	98.2
1/2		3.1	6.1	11.7	22.1	39.3	63.2	86.5	98.2	99.9
1		6.1	11.7	22.1	39.3	63.2	86.5	98.2	99.9	100
2		11.7	22.1	39.3	63.2	86.5	98.2	99.9	100	100
4		22.1	39.3	63.2	86.5	90.2	99.9	100	100	100
8		39.3	63.2	86.5	98.2	99.9	100	100	100	100
16		63.2	86.5	98.2	99.9	100	100	100	100	100

Source: Shurcliff (1981). Reprinted by permission.

material assembly deemed likely to contribute more than one-third of these allowable concentrations, and used in large quantities, was to be tested before acceptance. One desirable outcome of such testing and associated materials specifications is the possible avoidance (or shortening) of an anticipated flush-out of a completed building before occupancy.

5.4 ZONING FOR IAQ

After pollution control is implemented at the source (cleaner equipment, prohibiting smoking, careful material choices, etc.), remaining unavoidable pollutant sources should be identified. Then more sensitive building areas should be isolated from the key contaminators. This is sometimes difficult, as in "open offices" where walls are unwelcome but copying machines are essential. In such cases, the method is to erect as much of a barrier as possible around an offender, then *task ventilate* to remove the contaminated air immediately. Sometimes air pollution sources also produce unwanted sound, in which case the argument for a more complete barrier may become more compelling.

Many health-care and laboratory buildings have "clean" and "dirty" zones, and even separate circulation pathways. Differential air pressures are

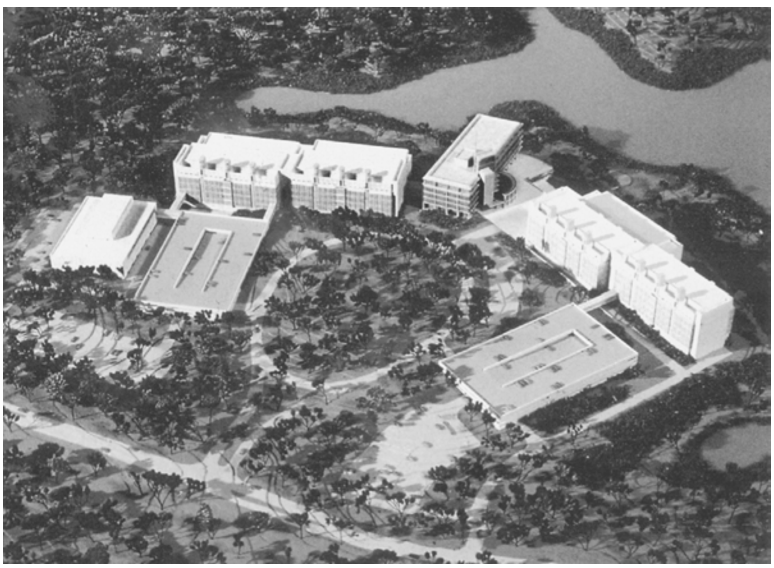


Fig. 5.2 *The campus of the U.S. Environmental Protection Agency at Research Triangle Park, North Carolina, features concentrated parking separate from the buildings. High exhaust stacks disperse air from laboratories; intakes are kept well away from exhaust. (Courtesy of Hellmuth, Obata + Kassabaum, Washington, DC.)*

TABLE 5.5 Air Quality Standards

PART A. **NATIONAL AMBIENT-AIR QUALITY STANDARDS FOR OUTDOOR AIR**						
	Long-Term Concentration Averaging			***Short-Term Concentration Averaging***		
Contaminant	**μg/m³**	**ppm**		**μg/m³**	**ppm**	
Sulfur dioxide	80	0.03	1 year	365	0.14	24 hours
Total particulate	75[a]	—	1 year	260	—	24 hours
Carbon monoxide				40,000	35	1 hour
Carbon monoxide				10,000	9	8 hours
Oxidants (Ozone)				235[b]	0.12[b]	1 hour
Nitrogen dioxide	100	0.055	1 year			
Lead	1.5	—	3 months[c]			

Source: U.S. Environmental Protection Agency.

PART B. **MAXIMUM INDOOR AIR CONCENTRATION STANDARDS AT EPA CAMPUS**	
Indoor Contaminants	**Allowable Air Concentration Levels[d]**
Carbon monoxide (CO)	<9 ppm
Carbon dioxide (CO_2)	<800 ppm
Airborne mold and mildew	Simultaneous indoor and outdoor readings
Formaldehyde	<20 μg/m³ above outside air
Total VOC	<200 μg/m³ above outside air
4 Phenyl cyclohexene (4-PC)[e]	<3 μg/m³
Total particulates	<20 μg/m³
Regulated pollutants	<National Ambient-Air Quality Standards (see Part A)
Other pollutants	<5% of TLV-TWA[f]

Source: Hellmuth, Obata + Kassabaum (2001).

[a]Arithmetic mean.

[b]The standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 ppm (235 μg/m³) is equal to or less than 1.

[c]A 3-month period is a calendar quarter.

[d]These levels must be achieved prior to acceptance of building. They do not account for contributions from office furniture, occupants, and occupant activity.

[e]4-PC is an odorous contaminant constituent in carpets with styrene-butadiene-latex rubber (SBR).

[f]TLV-TWA is threshold limit value, time-weighted average.

often maintained to discourage airflow from dirty to clean zones—with higher pressure in clean areas, lower pressure in dirty areas. Lower-pressure areas can be created simply by exhausting air from such spaces, as well as by limiting the volume of supply air. Higher-pressure areas can be created by installing makeup air equipment, as well as increasing the volume of supply air from the HVAC system.

On a site-planning scale, try to locate air intakes upwind from pollution sources. Because winds frequently change direction, this may be more a matter of adequate separation distance than direction. The most obvious example is a major air intake for a central HVAC system, which should be as far as possible from parking areas, delivery docks, and streets—and from the exhaust outlets from that same HVAC system or outlets from other building systems. Even exhaust outlets should be located carefully, because there is a possibility that outdoor air can be drawn into these exhaust openings. A mechanical equipment room is the typical location for both intake and exhaust; energy conservation devices such as heat exchangers benefit from close proximity of intake and exhaust. Most animals use the same "ducts" to breathe in and exhale, obviously inviting air reentrainment. For a building, however, separation of these openings is prudent design.

The campus for the EPA (Fig. 5.2) is an example of predesign planning for IAQ. This is a 1,000,000-ft² (92,900-m²) building complex serving a population of more than 2000 on 133 acres (54 hectares) of farm land that has reverted to second-growth hardwoods. Table 5.6 gives a summary of design decisions and their impact on IAQ. Some of the more

TABLE 5.6 Design Decisions and Impacts: EPA Campus, Research Triangle Park

Item	Decision	Impact on IAQ
Siting of building	Locate exhaust downwind from air intakes, separate by >100 ft (30 m) Maximize separation between parking areas and air intakes	Minimizes reentrainment of laboratory exhaust air at air intakes Reduces the potential for vehicular exhaust entering building
Location of parking garages	Locate parking structure away from the building	Reduces the potential for vehicular exhaust entering building
Laboratory exhaust stacks	Increase stack height to 30 ft (9 m) based on wind tunnel testing	Minimizes reentrainment of laboratory exhausts into air intakes
Radon	Site-specific testing confirmed low levels of radon	Confirmed that radon levels are safe
Delivery/loading zone	Maintain negative pressure in loading area, positive pressure in building	Eliminates entrainment of delivery vehicle exhaust
Landscaping	Low-maintenance and nonsporulating plants selected Plants used as a barrier to vehicle exhaust	Intake of spores, fertilizer, or chemicals entering building is reduced Minimizes entrainment of delivery vehicle exhaust
Laboratory fume hoods	Install flow gauges and alarms	Provides warning of air contaminants present in laboratory areas due to loss of flow
Acoustic insulation of ducts	Ductwork increased in size to reduce need for acoustical insulation; in select areas, mylar-coated duct silencers are used as ductwork transitions out of equipment rooms	Minimizes release of fibers into the airstream and possible contamination of the HVAC system (duct liners are difficult to monitor or to clean and can be sites of microbial growth)
Moisture accumulation	Install drain pans pitched toward drain pipe	Reduces moisture, which could result in introduction of bacterial contamination into HVAC system
Humidity control	No moisture carryover into system	Minimizes moisture in HVAC system and resultant bacterial contaminants due to moisture
Corrosion inhibitors	Inhibitors do not contain volatile amines	Eliminates exposure to certain air contaminants
System maintenance	Provide access panels at ductwork appurtenances and ample clearance around equipment	Maximizes ease of maintaining HVAC system
Outside ventilation rate	100% outdoor air in laboratories; 20 cfm (10 L/s) per person in offices Flexibility to increase ventilation rate 20% for unexpected sources	Maximizes occupant comfort and removal of air contaminants Minimizes possible occupant exposure to contaminants
Airflow efficiency	Minimum airflow rate set at 3 ACH for VAV system in office areas Flexible connections to room diffusers in open office areas	Increases air movement and ventilation effectiveness Facilitates modifications to enhance airflow as necessary
Air cleaning	ASHRAE 30% efficiency pre-filters with 85% final filters Flexibility to add scrubbers to laboratory exhaust Use bird-proofing mesh screen	Minimizes dust and other aerosols entering indoor air via the HVAC system Minimizes release of contaminants to ambient air Eliminates bird droppings and possible microorganism infection in the HVAC system
Thermal control	Building Automated Control system Fixed windows	Provides optimum control of temperature and pressure Prevents unconditioned air from entering building; maintains positive pressure in laboratories
Exhaust system	100% exhaust for photocopying rooms, laboratories, food preparation areas Photocopiers located within 10 ft (3 m) of exhaust vent	Eliminates potential to recirculate contaminants and odors through the building via the HVAC system Controls potential source of air contaminants; recirculated air is filtered prior to its return
Smoking	Designate building as nonsmoking	Eliminates exposure to secondhand smoke and recirculation of tobacco smoke via the HVAC system
Building materials, finishes, furnishings	Materials selected to minimize release of contaminants from products	Minimize occupant exposure to contaminants as a result of off-gassing from building materials, finishes, furnishings

Source: Hellmuth, Obata + Kassabaum, Architects, Washington, DC. This material was produced with U.S. government sponsorship through Order #70-2124-NTLX.

visible design consequences are the separation of parking and building, the concentration of parking in a structure (less impact on the existing landscape, more control of vehicle fumes), and the height of the exhaust stacks from the laboratories. Many other design decisions are hidden within the building's materials and HVAC system, as detailed in Table 5.6.

The topic of zoning includes decisions about local versus central equipment. Should individual exhaust fans be installed (creating selective lower-pressure areas) or a central exhaust fan (that can discharge up a very tall stack)? Should air cleaners be installed locally, where they can be selected according to the degree of pollution, or centrally, where they can be more easily and regularly maintained? What about heat exchangers for tempering incoming air: many smaller ones or one large one? The larger and more complex a building is, the more likely the need for a mix of local, specialized zones and a large, more general zone that is centrally served. Figure 5.3 explores the issue of the location of an office copier: at the edge, where task ventilation is easy, but plentiful daylight and a view may be "wasted" on this function, or away from the edge, where a central exhaust system is more likely to be utilized.

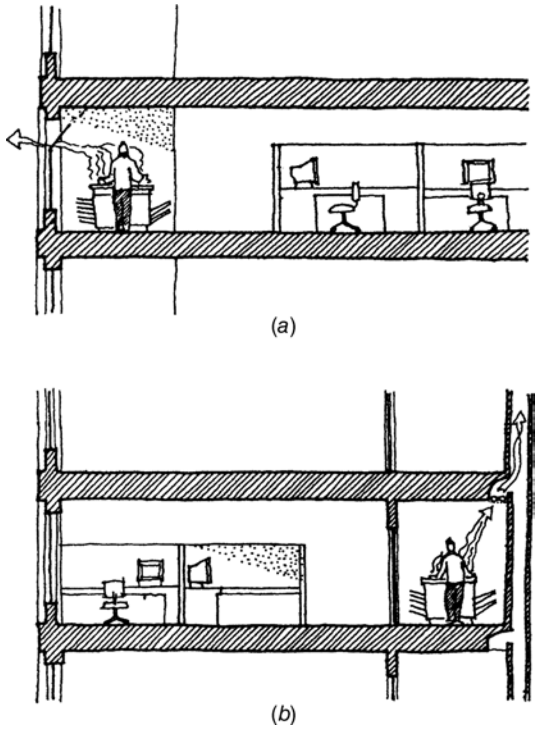


Fig. 5.3 *Zoning for IAQ: the office copier. This notorious source of VOCs can be located at the perimeter (a), where access to fresh air and direct exhaust is simple; however, perimeter space is prime real estate for daylight and views. If the copier is located in less-desirable interior space (b), exhaust air can create negative air pressure, drawing air from adjacent offices and containing the VOCs; longer runs of exhaust ducts are required.*

5.5 PASSIVE AND LOW-ENERGY APPROACHES FOR CONTROL OF IAQ

This section deals with passive ventilation for control of indoor air quality. Ventilation is an approach that assumes that "the solution to pollution is dilution." Another IAQ strategy, air cleaning, almost always involves forcing air through various filtering devices using active systems. Filters and other equipment associated with active approaches to ventilation and air cleaning are discussed in a following section.

(a) Windows

Operable windows are one of the oldest and most common "switches" of all. Passive ventilation through windows and skylights is influenced by the position of the open window; if wind strikes the glass surface in its open position, it will be deflected. The direction of the wind approaching the window is generally unpredictable. Also, whereas for simple ventilation (without cooling) it is usually desirable to keep wind *away* from people, for cooling at temperatures above the standard comfort zone, wind *across* the body is helpful (see Fig. 3.33). For these reasons, a window that can be opened in a variety of positions can be useful; some examples are shown in Fig. 5.4.

Perhaps the best aspect of operable windows is that they give the building occupants some control over the source of outdoor air. Perhaps the worst aspect is that they rarely offer any means of filtering this incoming air. They also can confound attempts by a central HVAC system to regulate airflow and the resulting pressure. Sometimes they admit air (windward side); at other times, they exhaust it (leeward side). Note that the EPA Campus (Fig. 5.2) elected to install fixed, not operable, windows.

Some windows offer more free area of opening than others of the same size. Figure 5.5 compares some common window types. The pattern of incoming flow is also highly influenced by the way in which these windows open. The outward flow is somewhat affected as well. Insect screens will reduce

(*a*) (*b*)

Fig. 5.4 *A window that can open in more than one position can enhance ventilation performance. (a) The window tilts from the top, directing the incoming air toward the ceiling; fresh air does not directly encounter workers within the space. (b) The window swings inward, allowing incoming air to move across people, enhancing warm-weather cooling. (Courtesy of Three Rivers Aluminum Company, Inc.)*

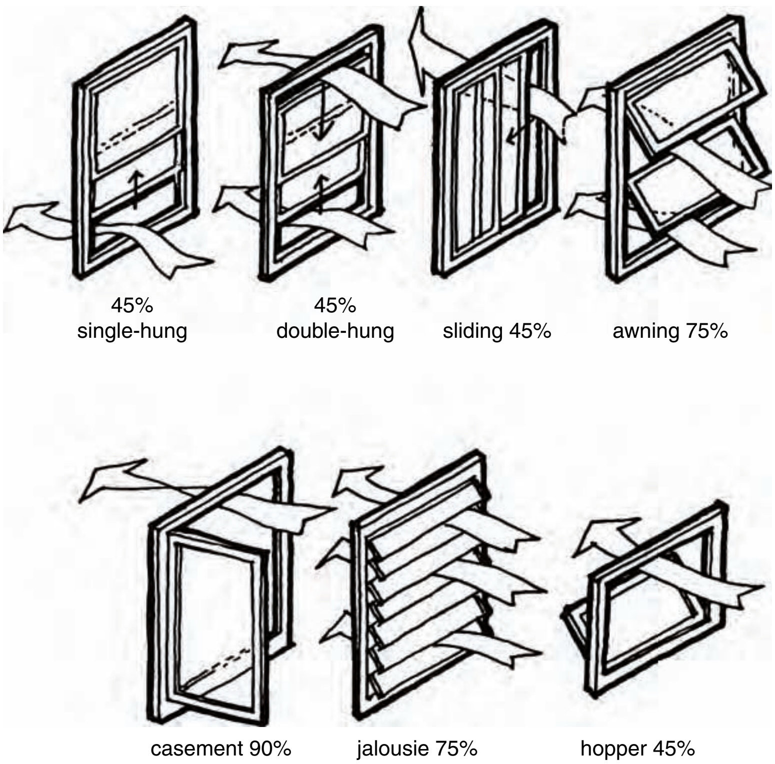


Fig. 5.5 *The percentage of actual openable area varies with the window type. (Reprinted by permission from Fuller Moore. 1994.* Environmental Control Systems: Heating, Cooling, Lighting*. McGraw-Hill Company. New York.)*

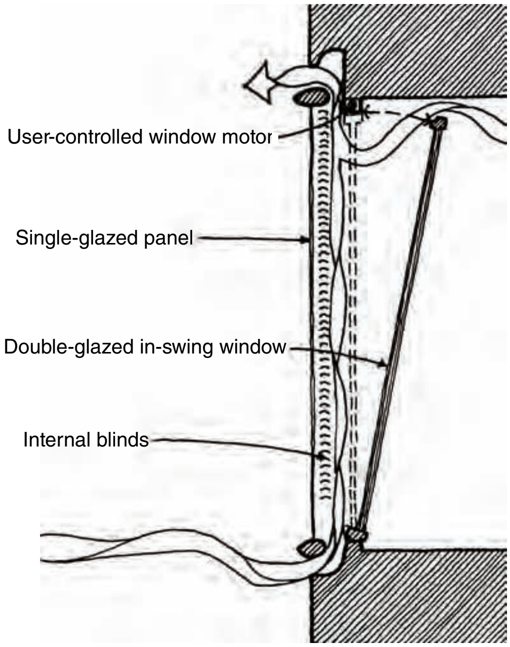


Fig. 5.6 *The Commerzbank is an addition to Frankfurt, Germany's, skyline. Operable windows in this 56-story tower are tilted in from the top by occupants, while a fixed outer pane with continuous venting slots at the top and bottom keeps air currents under control. Shown here in exhaust mode, the window can also supply fresh air to the office. Under adverse outdoor conditions, the building management system (BMS) locks the inner window in the closed position.*

the flow of air. Details of windows and screens are discussed in Chandra et al. (1986).

Windows work best in the presence of wind. In calm conditions, they may still admit—or exhaust—air due to the stack effect. The taller the building, the more pronounced this effect. Operable windows in very tall buildings have been shunned by designers until recently. The Commerzbank in Frankfurt, Germany, is a 56-story tower. Each office's exterior window (Fig. 5.6) is operable in temperate weather, and the occupant decides the degree of openness; a lock-out is controlled by a building management system (BMS). The full-height office window's outer skin consists of fixed single-glazed safety glass, with 5-in. (125-mm) ventilation slots all across the top and bottom. These serve the 8-in. (200-mm) wide cavity between the outer and inner window skins. The inner window is double-glazed, hinged at floor level, and has a motor-operated tilt-in mechanism at the top. Motorized blinds for solar shading are located within the cavity between the window skins. A central atrium provides a stack effect so that an open window is usually a source of incoming rather than exhaust air, although the top and bottom slots allow for a slight stack effect at each window.

(b) Stack Effect

Several applications of the principle that hot air rises are applicable to IAQ. Estimating airflow due to the stack effect is discussed in Chapter 10, along with more detailed calculations. Devices can be used to enhance the stack effect by creating suction when wind blows across the top of a stack. Probably the most common (available in chain-store catalogs) are wind-gravity or turbine ventilators (Fig. 5.7); typical performance characteristics are listed in Table 5.7. This is probably not the most effective topping device, however. Figure 5.8 compares volumetric airflow results for a turbine and several other ventilators with those for a simple open stack. The tests were done in a wind tunnel at the Virginia Polytechnic Institute.

Because the stack effect works more forcefully with increased height, intakes should be as low as

Fig. 5.7 *Two wind-gravity (turbine) ventilators accent the skyline of the addition to Barton Hall at the University of New Hampshire. These draw hot exhaust air from the auditorium; cool outdoor air is admitted through low windows and shutters in the auditorium's north wall. (Courtesy of Banwell White Arnold Hemberger & Partners, Inc., Hanover, NH.)*

TABLE 5.7 Turbine Ventilator Performance

Note: The combination of wind suction and stack effect produces the following exhaust capacities (in cfm) for various throat diameters and stack heights of turbine ventilators. Recommended spacing between ventilators is 20 ft.

IP UNITS																
Outdoor Wind Velocity: mph		2			4			6			8			10		
ΔT, indoors-outdoors °F		10	20	30	10	20	30	10	20	30	10	20	30	10	20	30
Turbine Throat Diameter in	Height Above Intake ft	Exhaust Capacity (cfm)														
6°	10	114	125	130	210	221	226	314	325	330	426	437	442	534	545	550
	20	122	135	144	218	231	240	322	335	344	434	447	456	542	555	564
	30	129	144	156	225	240	252	329	344	356	441	456	468	549	564	576
	40	135	152	166	231	248	262	335	352	366	447	464	478	555	572	586
10°	10	209	222	274	370	383	435	545	558	610	728	741	793	915	928	980
	20	234	269	301	395	430	462	570	605	637	753	788	820	940	975	1007
	30	254	301	328	415	462	489	590	637	664	773	820	847	960	1007	1034
	40	269	318	355	430	479	516	605	654	691	788	837	874	975	1024	1061
14°	10	333	383	422	558	608	647	804	854	893	1062	1112	1151	1324	1374	1413
	20	376	444	496	601	669	721	847	915	967	1105	1173	1225	1367	1435	1487
	30	413	496	560	638	721	785	884	967	1031	1142	1225	1289	1404	1487	1551
	40	444	539	614	669	764	839	915	1010	1085	1173	1268	1343	1435	1530	1605
18°	10	476	564	623	755	843	902	1071	1159	1218	1399	1487	1546	1737	1825	1884
	20	549	662	747	828	941	1026	1144	1257	1342	1472	1585	1670	1810	1923	2008
	30	611	747	853	890	1026	1132	1206	1342	1448	1534	1670	1776	1872	2008	2114
	40	662	819	941	941	1098	1220	1257	1414	1536	1585	1742	1864	1923	2080	2202
24°	10	716	874	978	1101	1259	1363	1522	1680	1784	1963	2121	2225	2412	2570	2674
	20	844	1046	1196	1229	1431	1581	1650	1852	2002	2091	2293	2443	2540	2742	2892
	30	954	1196	1384	1339	1581	1769	1760	2002	2190	2201	2443	2631	2650	2892	3080
	40	1046	1324	1542	1431	1709	1927	1852	2130	2348	2293	2571	2789	2742	3020	3238
30°	10	1139	1385	1545	1719	1965	2125	2379	2625	2785	3068	3314	3474	3769	4015	4175
	20	1342	1655	1890	1922	2235	2470	2582	2895	3130	3271	3584	3819	3972	4285	4520
	30	1514	1890	2185	2094	2470	2765	2754	3130	3425	3443	3819	4114	4144	4520	4815
	40	1655	2090	2430	2235	2670	3010	2895	3330	3670	3584	4019	4359	4285	4720	5060
36°	10	1613	1967	2201	2475	2829	3063	3418	3772	4006	4414	4768	5002	5428	5782	6016
	20	1901	2354	2692	2763	3216	3554	3706	4159	4497	4702	5155	5493	5716	6169	6507
	30	2148	2692	3115	3010	3554	3977	3953	4497	4920	4949	5493	5916	5963	6507	6930
	40	2354	2981	3470	3216	3843	4332	4159	4786	5275	5155	5782	6271	6169	6796	7285
42°	10	2183	2663	2998	3350	3835	4170	4645	5125	5460	6000	6480	6815	7365	7845	8180
	20	2588	3203	3668	3760	4375	4840	5050	5665	6130	6405	7020	7485	7770	8385	8850
	30	2928	3668	4243	4100	4840	5415	5390	6130	6705	6745	7485	8060	8110	8850	9425
	40	3203	4058	4723	4375	5230	5895	5665	6520	7185	7020	7875	8540	8385	9240	9905
48°	10	2868	3500	3925	4412	5044	5469	6078	6710	7135	7843	8475	8900	9638	10270	10695
	20	3378	4185	4785	4922	5729	6329	6588	7395	7995	8353	9160	9760	10148	10955	11555
	30	3817	4785	5535	5361	6329	7079	7027	7995	8745	8792	9760	10510	10587	11555	12305
	40	4185	5300	6175	5729	6844	7719	7395	8510	9385	9160	10275	11150	10955	12070	12945

TABLE 5.7 Turbine Ventilator Performance (*continued*)

Note: The combination of wind suction and stack effect produces the following exhaust capacities (L/s) for various throat diameters and stack heights of turbine ventilators. Recommended spacing between ventilators is 6 m.

SI UNITS																
Outdoor Wind Velocity: m/s		**0.9**			**1.8**			**2.7**			**3.6**			**4.5**		
ΔT, indoors-outdoors °C		**5.6**	**11.1**	**16.7**	**5.6**	**11.1**	**16.7**	**5.6**	**11.1**	**16.7**	**5.6**	**11.1**	**16.7**	**5.6**	**11.1**	**16.7**
Turbine Throat Diameter mm	**Height Above Intake mm**	**Exhaust Capacity (L/s)**														
150	3	54	59	61	99	104	107	148	153	156	201	206	209	252	257	260
	6	58	64	68	103	109	113	152	158	162	205	211	215	256	262	266
	9	61	68	74	106	113	119	155	162	168	208	215	221	259	266	272
	12	64	72	78	109	117	124	158	166	173	211	219	226	262	270	277
250	3	99	105	129	175	181	205	257	263	288	344	350	374	432	438	463
	6	110	127	142	186	203	218	269	286	301	355	372	387	444	460	475
	9	120	142	155	196	218	231	278	301	313	365	387	400	453	475	488
	12	127	150	168	203	226	244	286	309	326	372	395	412	460	483	501
350	3	157	181	199	263	287	305	379	403	421	501	525	543	625	648	667
	6	177	210	234	284	316	340	400	432	456	522	554	578	645	677	702
	9	195	234	264	301	340	370	417	456	487	539	578	608	663	702	732
	12	210	254	290	316	361	396	432	477	512	554	598	634	677	722	757
450	3	225	266	294	356	398	426	505	547	575	660	702	730	820	861	889
	6	259	312	353	391	444	484	540	593	633	695	748	788	854	908	948
	9	288	353	403	420	484	534	569	633	683	724	788	838	883	948	998
	12	312	387	444	444	518	576	593	667	725	748	822	880	908	982	1039
610	3	338	412	462	520	594	643	718	793	842	926	1001	1050	1138	1213	1262
	6	398	494	564	580	675	746	779	874	945	987	1082	1153	1199	1294	1365
	9	450	564	653	632	746	835	831	945	1034	1039	1153	1242	1251	1365	1454
	12	494	625	728	675	807	909	874	1005	1108	1082	1213	1316	1294	1425	1528
760	3	538	654	729	811	927	1003	1123	1239	1314	1448	1564	1639	1779	1895	1970
	6	633	781	892	907	1055	1166	1219	1366	1477	1544	1691	1802	1874	2022	2133
	9	715	892	1031	988	1166	1305	1300	1477	1616	1625	1802	1941	1956	2133	2272
	12	781	986	1147	1055	1260	1420	1366	1571	1732	1691	1897	2057	2022	2227	2388
910	3	761	928	1038	1168	1335	1445	1613	1780	1890	2083	2250	2360	2562	2729	2839
	6	897	1111	1270	1304	1518	1677	1749	1963	2122	2219	2433	2592	2697	2911	3071
	9	1014	1270	1489	1420	1677	1877	1865	2122	2322	2335	2592	2792	2814	3071	3270
	12	1111	1407	1638	1518	1814	2044	1963	2259	2489	2433	2729	2959	2911	3207	3438
1070	3	1030	1257	1415	1581	1810	1968	2192	2419	2577	2831	3058	3216	3476	3702	3860
	6	1221	1512	1731	1774	2065	2284	2383	2673	2893	3023	3313	3532	3667	3957	4176
	9	1382	1731	2002	1935	2284	2555	2544	2893	3164	3183	3532	3804	3827	4176	4448
	12	1512	1915	2229	2065	2468	2782	2673	3077	3391	3313	3716	4030	3957	4360	4674
1220	3	1353	1652	1852	2082	2380	2581	2868	3167	3367	3701	3999	4200	4548	4846	5047
	6	1594	1975	2258	2323	2704	2987	3109	3490	3773	3942	4323	4606	4789	5170	5453
	9	1802	2258	2612	2530	2987	3341	3316	3773	4127	4149	4606	4960	4996	5453	5807
	12	1975	2501	2914	2704	3230	3643	3490	4016	4429	4323	4849	5262	5170	5696	6109

Source: Reprinted courtesy of Western Ventilating Equipment, Inc., Los Angeles. SI units appended by authors of this book (they are not part of original source).

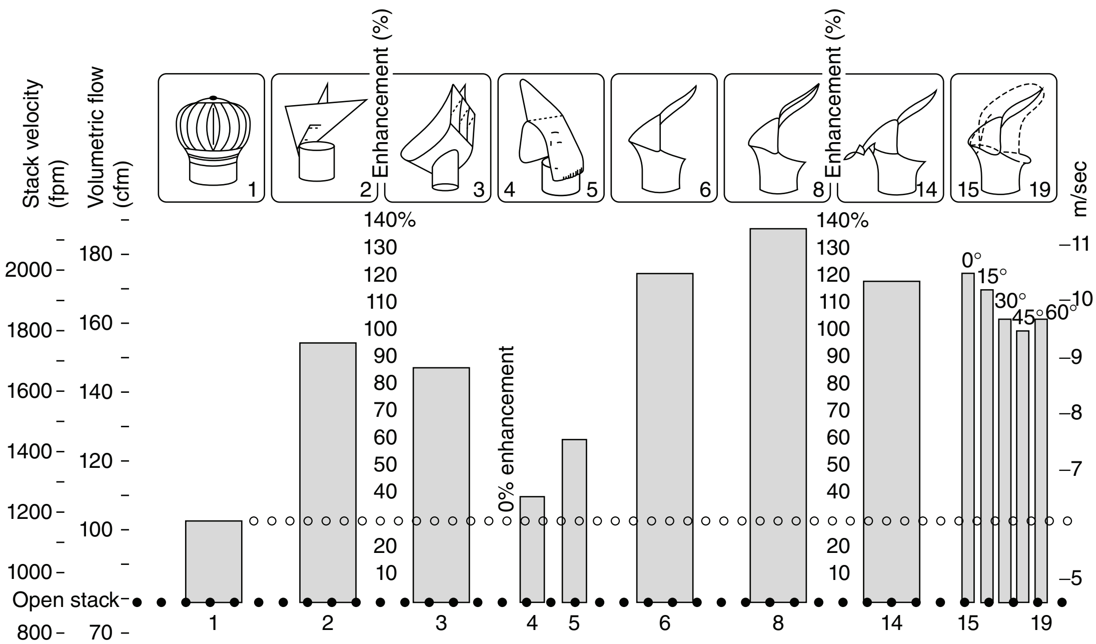


Fig. 5.8 *Performance of some passive ventilators compared to a simple open stack. The popular turbine ventilator is identified as #1 but is outperformed by many other devices. (From the work of R. P. Schubert and Philip Hahn; reprinted from* Progress in Passive Solar Energy Systems*; © 1983. By permission of the publisher, American Solar Energy Society, Boulder, CO.)*

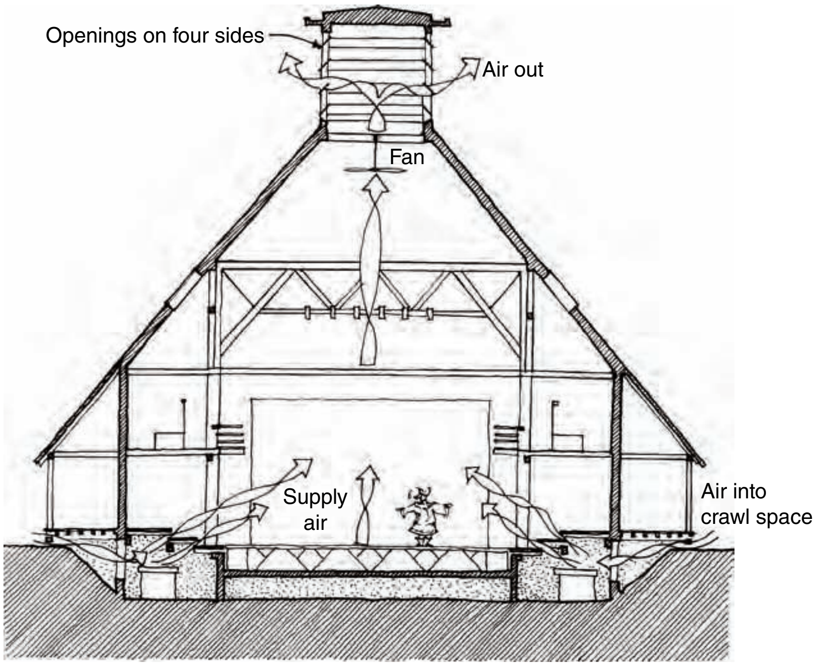
possible. When these openings are near the ground, precooling of summer intake air is possible. The Olivier Theatre at the Bedales School in rural Hampshire, England (Fig. 5.9), uses a gently sloping site to similar advantage. The tightly packed audience of a theater generates considerable heat, as do the lights. For this theater, the maximum acceptable temperature around the audience is about 77°F (25°C); the heat produced by people and lights provides a temperature increase of about 12.6°F (7°C). Therefore, whenever the outdoor temperature is above 64°F (18°C), cooling of the incoming air is needed.

In this theater, air is introduced to an "undercroft" (crawl space) with a concrete floor, on which are built many concrete block walls, forming an indirect path for the incoming air. This undercroft is cooled by night ventilation, and thus is made ready for the next event's heat gains. The inlet openings are 5% of the theater floor area; the surface area of the undercroft is 32 ft^2 (3 m^2) per person. The audience of 270 people is ventilated and cooled by the air rising from this undercroft, through openings that total 3.5% of the floor area. Gaining heat, the air rises toward the central cupola, aided when necessary by a "punkah" fan, and exits through four louvered sides of the cupola, with a total outlet area of 6% of the floor area. The overall height of this stack is 51 ft (15.5 m); a maximum of 15 ACH is expected at around 5F° (3C°) difference (warmer inside than outside). This ventilation–cooling system is silent and utilizes no refrigerant. In the heating season at partial occupancy, the stack outlets are closed, and the fan can be run in reverse to send collected warm air downward to the floor.

(c) Under-Slab Ventilation

Although the Olivier Theatre uses the ground's coolth to its advantage, there are some places where the ground contains radon (or other soil gases). A map of the United States (Fig. 5.10) shows the relative risk of radon, a long-term harmful gas, on a county-by-county basis. Buildings on former industrial sites or landfills could be threatened by other dangerous soil gases. Even ordinary sites can be threatened by methane gas from a leaking sewer line. A precaution against soil gas is to design for a *passive subslab depressurization system*. This involves at least one 4-in. (100-mm) pipe open at both ends. The lower end is set into a

(*a*)



(*b*)

Fig. 5.9 *Stack ventilation caps the Olivier Theatre at the Bedales School in rural Hampshire, England. (a) View from the east. (Photo by VIEW/Dennis Gilbert.) (b) Section shows the openings that admit outdoor air to the concrete "undercroft," where it is cooled, then admitted below seats to the auditorium; gaining heat, it rises (assisted when necessary by a punkah fan) and exits out the four-sided dampered openings in the cupola. (Designed by Fielden Clegg Architects, Bath, Avon; engineering by Max Fordham and Partners, London.)*

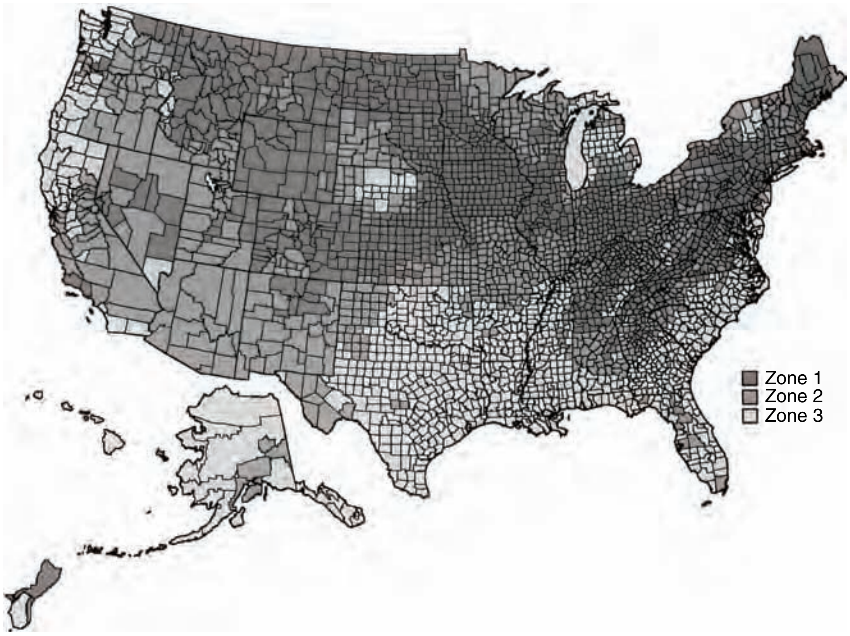


Fig. 5.10 *Relative risks of high radon levels in the soil by county in the United States. The darker the zone, the higher the risk (zone 1, for example, presents more risk than zone 2). (Courtesy U.S. Environmental Protection Agency. From* A Guide to Radon. *Environmental Health Center, National Safety Council. Washington, DC. 1996.)*

layer of clean, crushed rock at least 4 in. (100 mm) thick that lies immediately below the floor slab. The object is to allow air within this rock layer to enter the open end of the pipe. The slab is poured and carefully sealed around the pipe, and the pipe is extended (via interior walls) through the roof, where it can vent radon and other soil gases to a safer place. Heat from the building drives the stack effect within this pipe.

(d) Preheating Ventilation Air

Fresh air brought directly into a space during the winter will improve IAQ, but at the expense of thermal comfort. Several passive or low-energy strategies to mitigate this problem are available. The office building in Fig. 5.11 is surrounded by a 4-ft-wide (1.2-m) cavity between the inner and outer glass surfaces. Air within this cavity is heated, both by the sun and by indoor heat sources, and rises out of a damper-controlled opening. Although this building does not utilize such heated air for ventilation, it demonstrates the possibility of such an approach.

The use of a south-facing wall as a winter preheating device with an (unglazed) *transpired collector* (available as SolarWall®) is illustrated in Fig. 5.12. Aluminum sheeting, specially finished for solar absorption and penetrated by thousands of tiny holes, is the exterior surface. Behind this is a cavity kept under negative pressure by a fan. Outdoor air is drawn through the holes, heated by the dark outer surface, and drawn up the cavity to the fan and then on to the space. Insulation and the interior surface complete the south wall. Thus, heat loss from the building through the south wall is recaptured by the inflowing outside air. In summer, a fan draws air directly from the outside, bypassing the solar cavity. The holes at the top of the wall serve as outlets for the stack effect produced by the solar gains through the outer surface. There are numerous installations around the world—one of the largest, at 108,000 ft^2 (10,034 m^2), is for an aircraft manufacturer in Quebec, Canada. For the design procedure, see NREL (1988).

Another approach to both residential winter ventilation and heat exchange is the *breathable wall* combined with an exhaust air heat pump. This system depends upon a house being under negative pressure, which is ensured by forced exhaust air. A heat pump then takes heat from the exhaust air and delivers that heat either for space heating or domestic water heating. The fresh air to replace that being

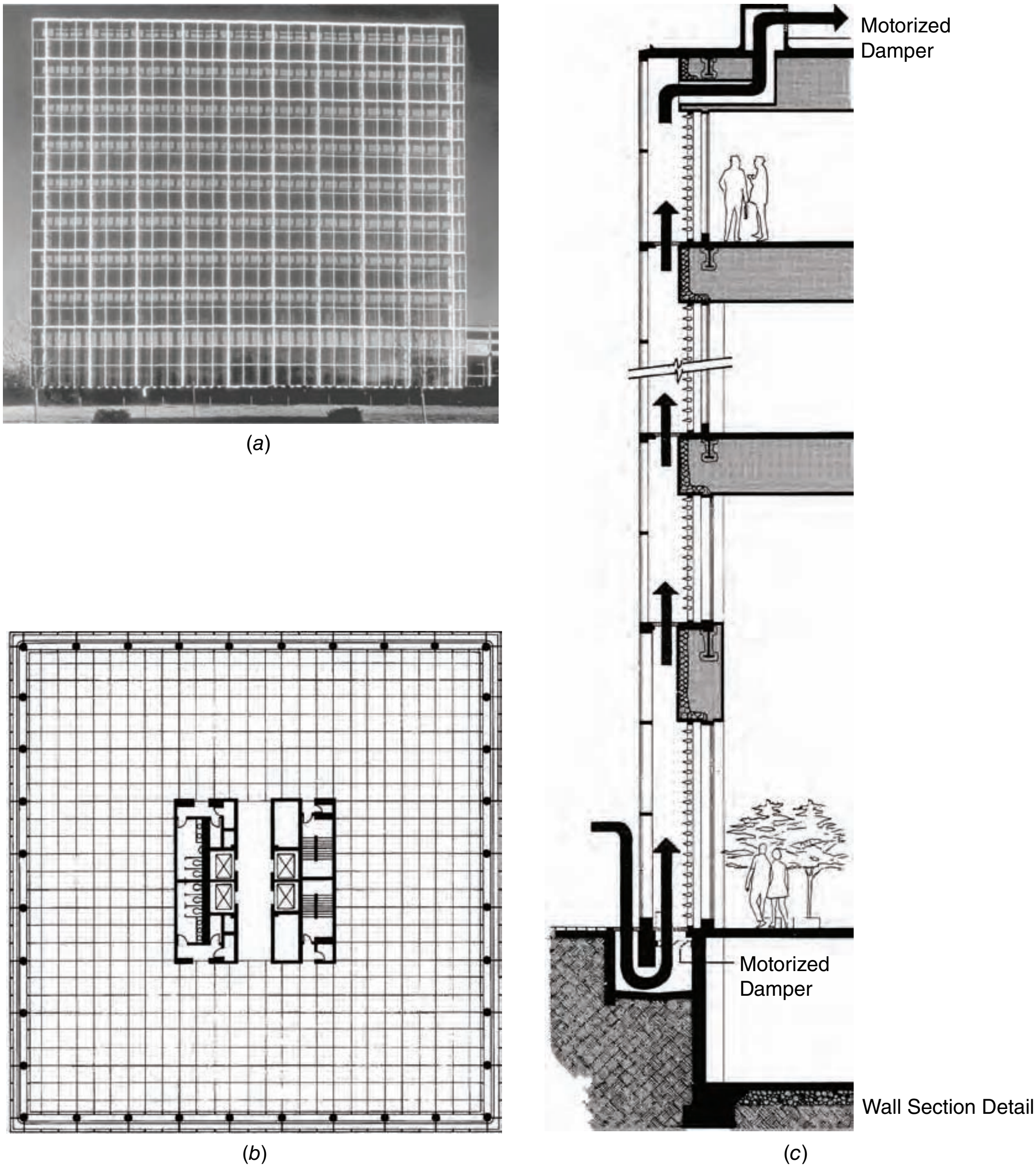
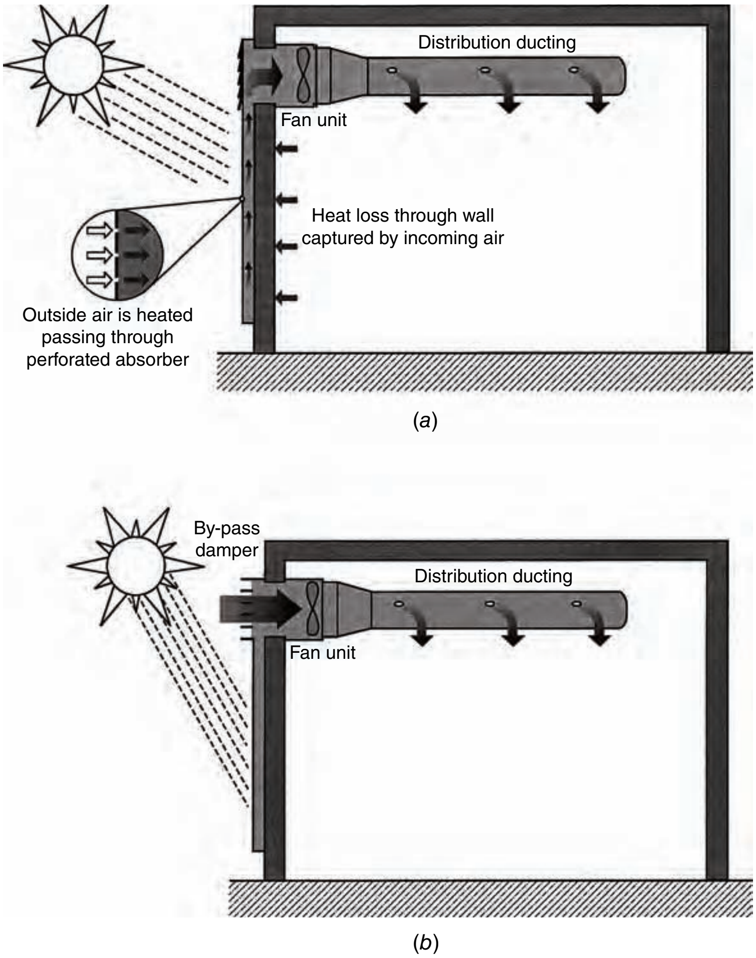


Fig. 5.11 *The Occidental Chemical Corporate Office Building, Niagara Falls, New York. (a) Fully exposed to sun and wind despite its downtown site, the building appears as a conventional curtainwall box. (b) An ordinary-looking plan with a central core and suspended ceilings. (c) On all four sides, a 4-ft (1.2-m) cavity allows for maintenance of movable daylight louvers and window washing, as well as for ample natural ventilation by the stack effect. Although cavity airflow is released at the roof, it could be utilized during winter as tempered fresh air to the interior. (Architects: Cannon Design, Inc.)*

expelled is drawn in through the outside walls by a unique combination of fiberglass lap siding board, fiberglass insulation batts, breathable sheathing, and *no* vapor retarder. This allows a slow, steady stream of cold air to enter, be warmed by the insulation, then enter the house. More information is available from the National Research Council Canada.

5.6 ACTIVE APPROACHES FOR CONTROL OF IAQ

This section concerns equipment that moves, heats or cools, humidifies or dehumidifies, and cleans air. A large range of capacities is involved, from room-sized to central whole-building air handling.



Interactive Animation

Fig. 5.12 *Winter preheating of fresh air on a south wall using an unglazed transpired collector (a). Tiny holes in the aluminum skin admit air to a cavity outside the wall's insulation, where it is preheated by sun on the dark aluminum, as well as by heat escaping through the insulation. A fan draws this air to a supply plenum, after which it is distributed to the space. In summer (b), the fan draws directly from the outside, and the collector is self-ventilated by the stack effect. (Courtesy of the National Renewable Energy Laboratory.)*

A general note about heating and cooling system choice: Acceptable IAQ will be easier to achieve if the heating and cooling systems utilize forced air motion, because some filtering is built into the air-handling equipment. However, separate air-cleaning systems are becoming increasingly common, so radiant heating systems with separate forced-air cleaning can yield high IAQ (given adequate outdoor air). For cooling, an economizer cycle can provide up to 100% outdoor air at times, and cooling by night ventilation of thermal mass provides many complete air changes during the nightly building maintenance activities that are so fume-producing. Evaporative cooling can provide a continuous flow of outdoor air.

(a) Exhaust Fans

Exhaust fans remove air that is odorous and/or excessively humid before it can spread beyond bathrooms, kitchens, or process areas, creating a negatively pressured area that further limits the spread of undesirable air. In buildings with heating systems without air motion (radiant heating), exhaust fans are often the only built-in devices for moving air. They are often very noisy, which is sometimes useful for covering noises associated with bathrooms, but also noisy enough to discourage their use over long periods of time. In its most simple application, the exhaust fan is a stand-alone device, with no thought about where the replacement air will be drawn from, and rarely much concern about where this unwanted air will be discharged to. (Discharge into attics, basements, or crawl spaces is prohibited by code.)

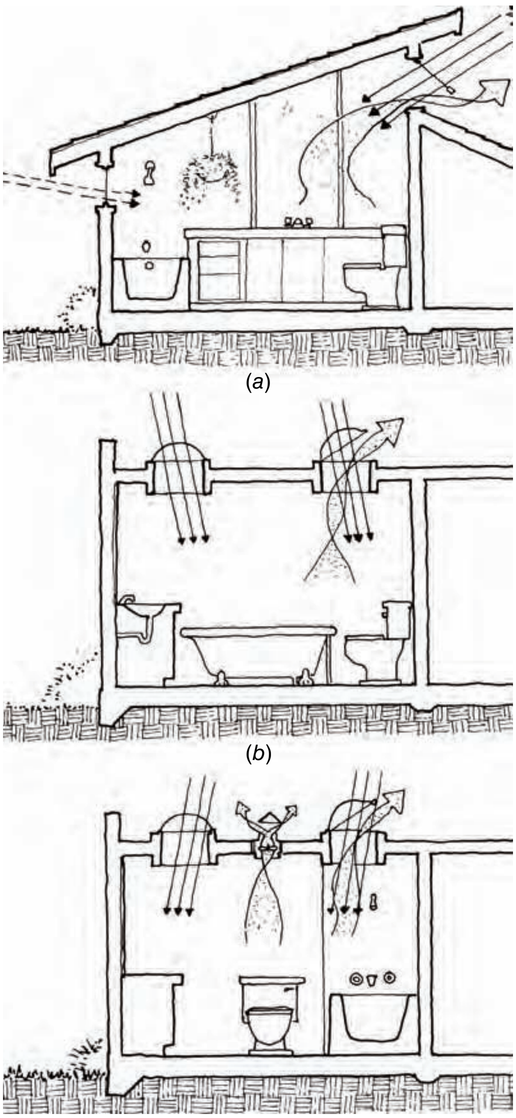
ANSI/ASHRAE Standard 62.2-2013, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*, requires intermittent (user-controlled) exhaust fans of at least 50-cfm (25-L/s) capacity for bathrooms and 100 cfm (50 L/s) for kitchens. The intakes for these fans should be as close to the source of polluted air as possible so as not to drag such air across other locations before it leaves the space. In kitchens, this is directly above the range (grease, odors, and water vapor); in bathrooms, in the ceiling above the toilet and shower areas to remove the moist air. Some options are shown in Fig. 5.13.

A more comprehensive approach in a residence includes the addition of a *principal exhaust fan*, which should be centrally located (drawing from the greatest space), quiet, and suitable for continuous use. Its exhaust capacity should be at least 50% of the entire system's capacity. In turn, this entire capacity is typically no less than 0.3 ACH. When this principal exhaust fan is operating, outdoor air must be brought in, tempered, and circulated throughout the residence. The tempering can be done by mixing with indoor air or by heating. Figure 5.14 shows two approaches to whole-house exhaust, one for forced-air systems and one without forced air motion.

This additional continuous exhaust capacity may cause problems of inadequate air for, or spillage of fumes from, combustion equipment. Such equipment (furnaces, stove-top barbecues, etc.) with a net exhaust greater than 150 cfm (75 L/s) must be provided with a makeup air fan that turns on/off with the equipment.

(b) Heating/Cooling of Makeup Air

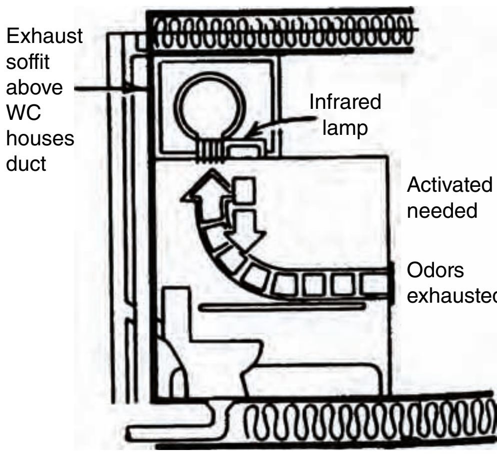
Where climates are mild and/or energy is inexpensive, special equipment (Fig. 5.15) other than heat



(*a*)

(*b*)

(*c*)



(*d*)

Fig. 5.13 *Options for exhaust air from toilet rooms: (a) Daylight enters from the sides; incoming air from the lower window picks up heat and moisture near the ceiling and exits through a high clerestory. (b) Two skylights admit daylight; one exhausts hot, moist air at the ceiling. Makeup air will be needed from the adjacent rooms. (c) Adding an exhaust fan will ensure negative pressure in the bathroom, isolating moisture and odors from the adjacent rooms. (d) In public toilet rooms, exhaust directly above toilets is desirable. In cold weather, small radiant heat lamps with timer switches could add task heat.*

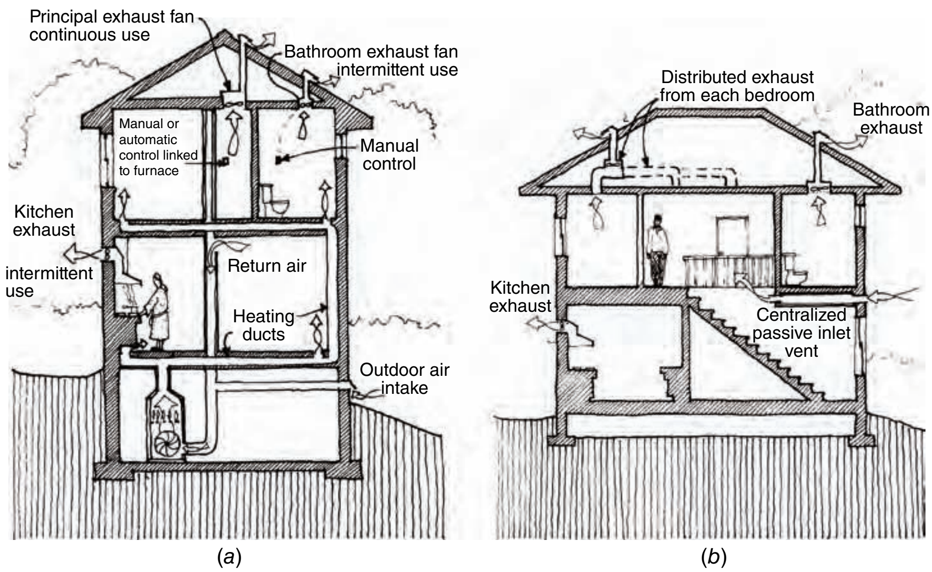


Fig. 5.14 *Ensured ventilation for residences. (a) Ventilation system with forced-air heat. (b) Partially distributed exhaust system with a vent. (Based upon Canadian Research Council studies.)*

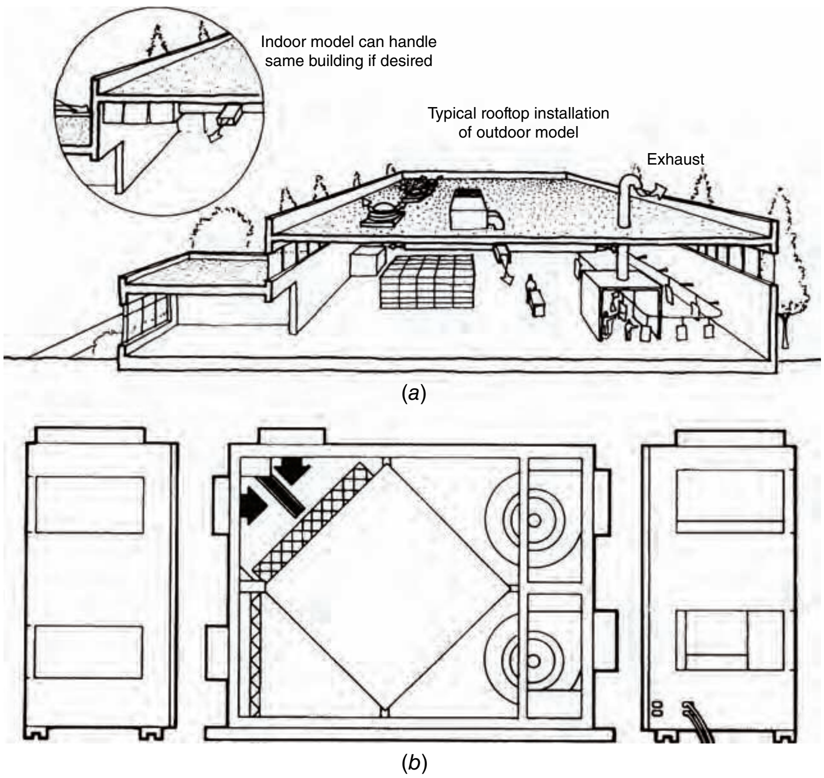


Fig. 5.15 *Makeup air heaters/coolers. (a) Distributed on a factory roof, these units prevent negative indoor air pressures by providing replacement (makeup) air for the air that is exhausted from processes indoors. Often, a separate heating/cooling system will be used for gains or losses through the building skin. (b) Heat-recovery ventilator, utilizing a cross-flow core, serves from 200 to 900 cfm (100 to 450 L/s), with supply air entering at a temperature 0.6 to 0.8 that of exhaust air temperature. (© Conservation Energy Systems, Minneapolis, MN.)*

exchangers can be used to heat and/or cool a particularly large quantity of makeup air. Especially common in factories or laboratory buildings with high exhaust air requirements, these simple devices often supplement the building's main heating/cooling system, which deals primarily with heat gains/losses through the building skin. In warm, dry climates, evaporative coolers are often used for makeup air because they are already designed to utilize 100% outdoor air. Even in hot and more humid climates, *indirect evaporative cooling* can help lower the temperature of makeup air. In Fig. 5.16, outdoor air is at 104°F (40°C) and 10% RH (point A). Two streams of outdoor air are involved. An evaporative cooler cools one air stream along a constant wet-bulb temperature line to point B, where it is now 70% RH but considerably cooler at 73°F (23°C): in the comfort zone, but warm and humid. At this point, it enters an air-to-air heat exchanger (see Section 5.6*c*). The other outdoor air stream enters the other side of this heat exchanger, again at point A conditions. As the two streams exchange heat, they move toward the same temperature: The evaporatively cooled stream moves from point B to point C, about 86°F (30°C) and 42% RH and is then exhausted. On the other side, outdoor air moves from point A to point D, about 91°F (33°C) and 16% RH. This second air stream is *indirectly evaporatively cooled*. Although it is still well above the comfort zone, it can then be either cooled by typical refrigerant systems or evaporatively cooled until it reaches the comfort zone.

(c) Heat Exchangers

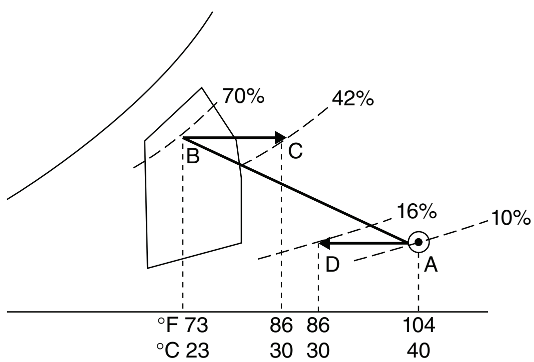
As the tightness of construction increases and fewer air changes per hour (ACH) occur from infiltration (unintended air leaks), forced ventilation becomes more attractive as a means of reducing indoor air pollution. When a heat exchanger is used, it is possible to maintain an adequate supply of fresh air without severe energy consumption consequences. Figure 5.17 illustrates the basic principle of a simple air-to-air heat exchanger that is becoming increasingly common for tightly built small buildings. Note that the outgoing and incoming air streams must be adjacent.

Some commercially available heat exchangers are capable of extracting 70% or more of the heat from exhaust air. The lower the volume of airflow, the higher the efficiency. Table 5.8, Part A, shows representative sizes, airflows, and efficiencies for these devices. For the best diffusion of incoming fresh air through a building, the heat exchanger should be incorporated at the central forced-air fan (Fig. 5.17*b*). When a central forced-air system is not available, heat exchangers can be placed at various points in a building; typically, each heat exchanger is then equipped with its own fan. These may serve as makeup air units that are more energy-efficient than the devices discussed in Section 5.6(b).

Some cautions about air-to-air heat exchangers:

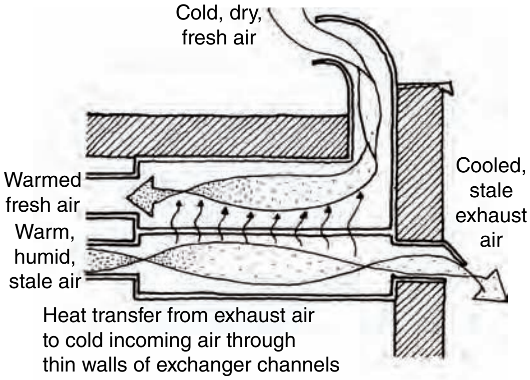
1. Avoid using them on exhaust air streams that are contaminated with grease, lint, or excessive moisture (through cooking and clothes drying in particular) because clogging, frosting, and fire-hazard problems can develop.
2. In colder winter conditions, a built-in defroster, which will consume energy, will be needed.
3. Carefully locate the outdoor fresh air intake. Keep this intake as far as possible from the exhaust air outlet, to avoid drawing contaminated exhaust air back into the building. Keep the intake away from pollution sources such as vehicle exhaust, furnace flues, dryer and exhaust fan vents, and plumbing vents.

A student housing complex in Greensboro, North Carolina, utilizes heat exchangers on the exhaust air from bathrooms (Fig. 5.18). These exhaust devices are called *energy recovery ventilators* (ERVs). Each floor of the three-story complex has four apartments, each with 1078-ft^2 (100-m^2) floor area and 8-ft (2-m) ceilings. Each apartment

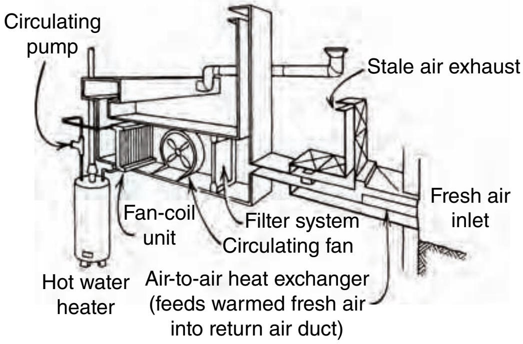


Interactive Animation

Fig. 5.16 *Indirect evaporative cooling can precool fresh air. The psychrometrics of the process.*



(*a*)



(*b*)

(*c*)

Fig. 5.17 *Air-to-air heat exchangers are particularly helpful in cold weather. (a) The basic principle of operation. (b) A superinsulated home is heated by coils fed from the domestic water heater, plus a heat exchanger to preheat incoming cold air. (Reprinted by permission of Alberta Agriculture, Home and Community Design Branch,* Low Energy Home Designs; *© 1983 by Brick House Publishing Co.) (c) Fan-powered heat exchanger utilizing a heat/moisture exchange wheel (see also Fig. 5.20). This model is adjustable from 70 to 200 cfm (35 to 100 L/s), can be ceiling-, wall-, or floor-mounted, and operates at 75% to 80% thermal efficiency. (Courtesy of Air Xchange, Inc., Rockland, MA.)*

TABLE 5.8 Representative Heat Exchanger Data for Smaller Buildings

PART A. **AIR-TO-AIR SENSIBLE HEAT EXCHANGERS**				
Approximate Size[a] L × W × H		***Airflow Range***		***Temperature Recovery at 32°F (0°C)***
in.	**mm**	**cfm**	**L/s**	
21 × 13 × 25	535 × 330 × 630	50–120	25–60	70%
34 × 17 × 21	865 × 435 × 530	75–225	35–110	80%
53 × 17 × 21	1335 × 435 × 530	75–225	35–110	93%
47 × 20 × 37	1195 × 505 × 940	350–700	165–330	65%

Source: Conservation Energy Systems, Inc., Saskatoon and Minneapolis.

PART B. **AIR-TO-AIR SENSIBLE + LATENT HEAT EXCHANGERS**				
Approximate Size[b] L × W × H		***Airflow Range***		***Wheel Efficiency***
in.	**mm**	**cfm**	**L/s**	
46 × 32 × 24	1170 × 815 × 610	500–1000	235–470	84–82%
54 × 48 × 34	1375 × 1220 × 865	600–1600	285–760	87–80%
		1600–2300	760–1090	75–70%
67 × 67 × 43	1705 × 1705 × 1095	1750–3250	830–1535	85–80%
		3000–4500	1420–2125	76–71%
124 × 84 × 60[c]	3150 × 2135 × 1525	3500–6500	1660–3070	85–80%
		6000–9000	2835–4250	76–71%

Source: Greenheck Fan Corporation, Schofield, WI.

[a]Access to one face (L × W) is needed for servicing.

[b]Several arrangements (interior and rooftop) are available; dimensions do not include service clearance access, supply hoods, or exhaust hoods.

[c]This unit contains two wheels.

has its own air-to-air ERV that accepts air from the two small bathrooms in the apartment. Control is by individual switches in the bathrooms. Prefiltered outdoor air is drawn into the ERV, exchanging heat with the outgoing exhaust air. This fresh air is then fed directly into the air handler for each apartment's heat pump, adjacent to the ERV. Thus, the bathrooms are under negative pressure relative to the rest of the apartment. Outside, the fresh air intake is located high on the wall, the exhaust outlet lower. Intake and outlet locations on the walls are separated by a minimum of 8 ft (2 m).

A *heat pipe* (Fig. 5.19) also transfers sensible heat between adjacent air streams. Within the heat pipe, a charge of refrigerant spends its life alternately evaporating, condensing, and migrating by capillary action through a porous wick. Because the only thing that moves is the refrigerant and it is self-contained, no maintenance and long life are likely. Efficiency ranges from 50% to 70%; modular sizes are available to 54 in. × 138 in. × 8 rows deep (1.4 × 3.5 m).

Heat pipes can assist in the dehumidification and cooling of incoming air. This potentially energy-intensive process often overcools the air to "wring out" (condense) water, then reheats the air. The heat pipe precools the air (subtracting heat) before the cooling coil, then warms it (adding heat) after the cooling coil. No energy input is required. A configuration of the heat pipe for this task is shown in Fig. 5.19*b*.

Energy transfer wheels (Fig. 5.20) go further than the two preceding devices in that they transfer latent as well as sensible heat. In winter, they recover both sensible and latent heat from exhaust air; in summer, they cool and dehumidify the incoming fresh air. Seals and laminar flow of air through the

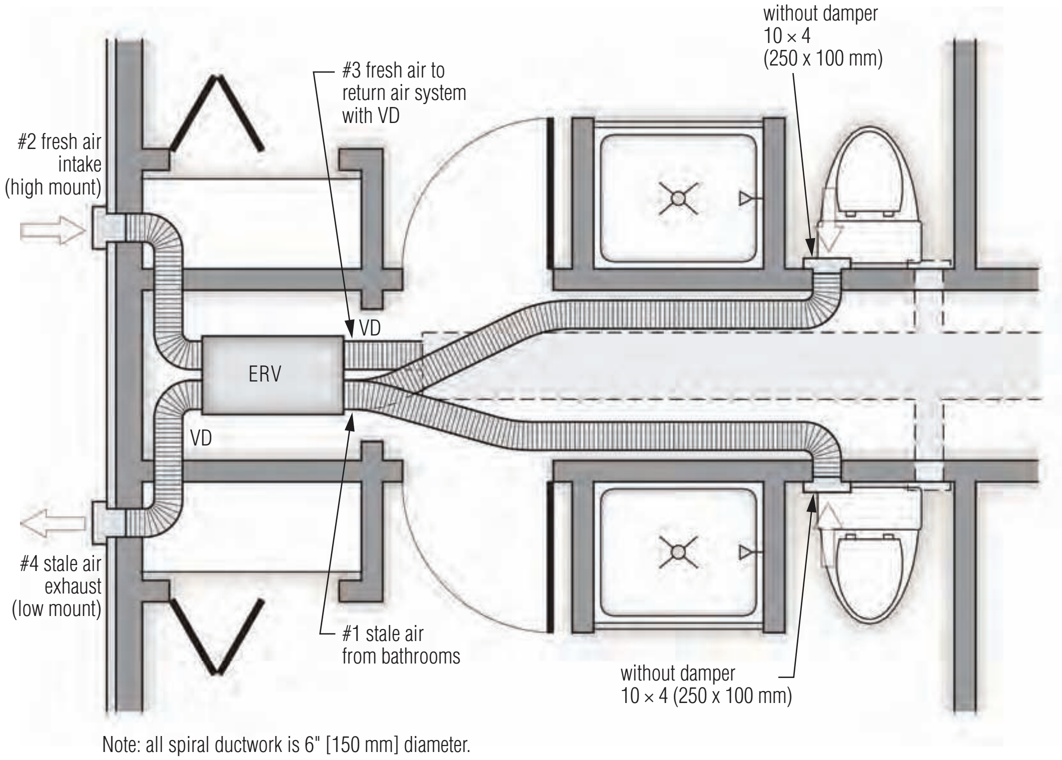


Fig. 5.18 *Energy recovery ventilator (ERV) serves two small bathrooms (a) in a student housing complex in Greensboro, North Carolina. The ERV is activated by switches in either bathroom. Air is drawn out beside the water closet and exchanges heat (at about 85% efficiency) with incoming fresh air. This tempered fresh air is then mixed with some return air and fed directly to the indoor unit of a heat pump (b) located above the ERV. The supply air is then fed to other rooms, ensuring a negative pressure in the bathroom while the ERV operates. Each of 16 apartments has its own ERV and heat pump. (Design by Harry John Boody, Jamestown, NC.)*

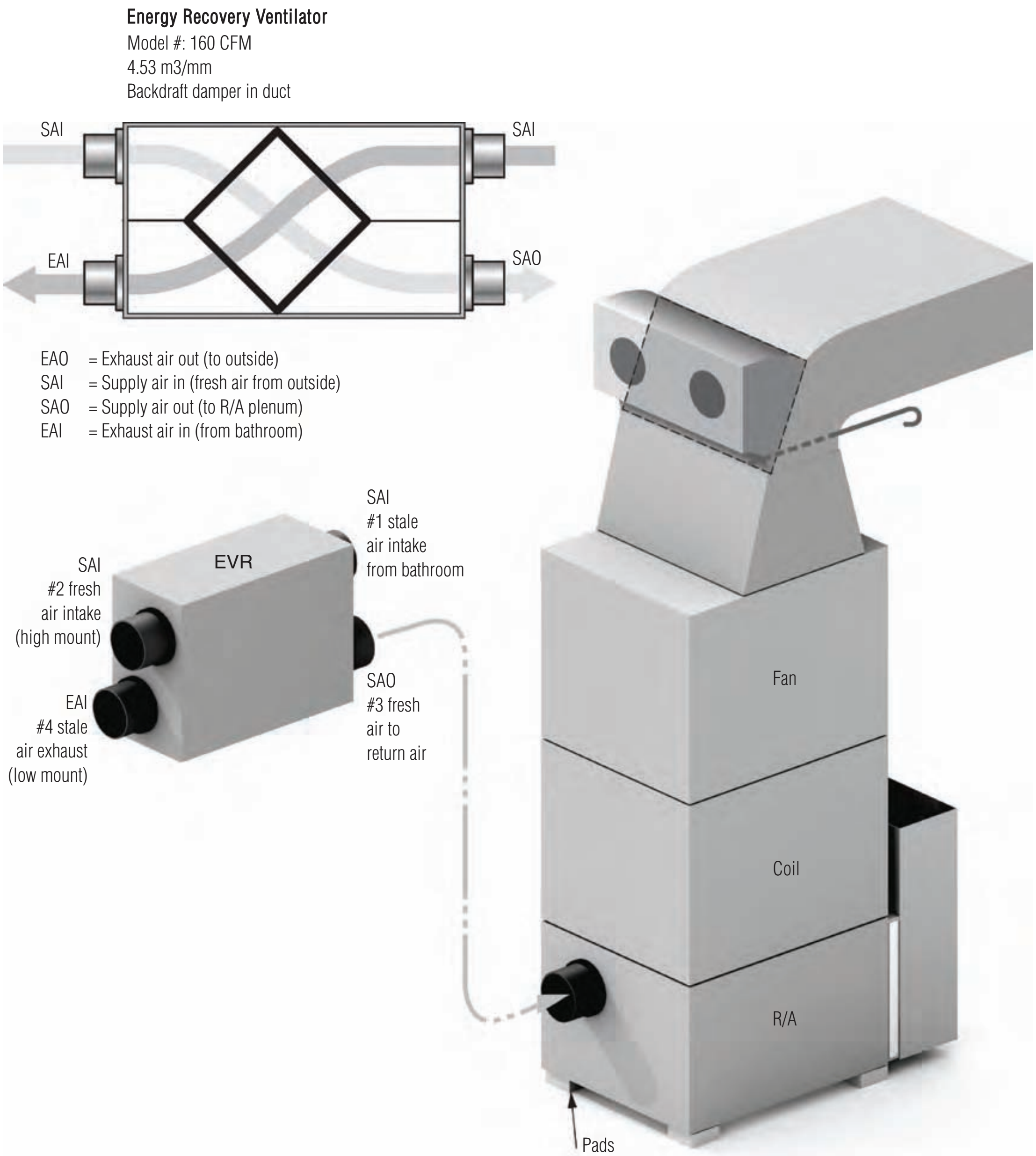


Fig. 5.18 *(continued)*

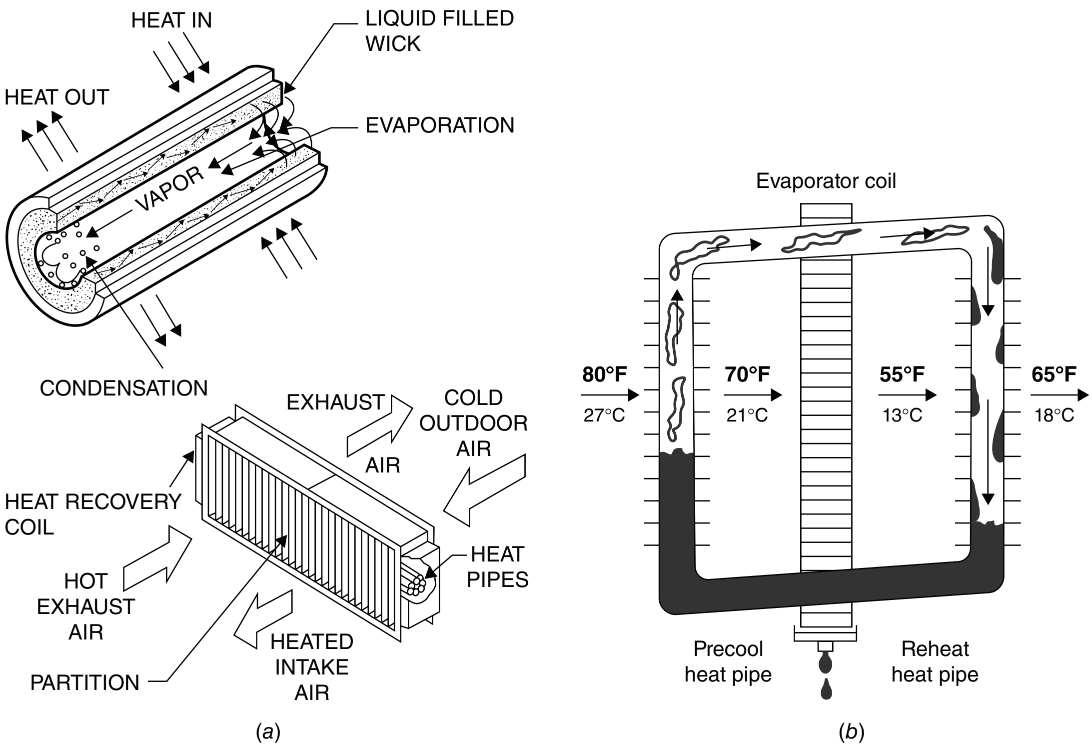


Fig. 5.19 *The heat pipe is a self-contained device with no moving parts. (a) It silently transfers sensible heat between adjacent fresh-air intake and stale-air exhaust air streams. (b) The heat pipe can increase moisture removal by first precooling incoming hot air before it reaches the cooling coils. Then the heat is returned to the cooled air, bringing it to a temperature–humidity combination acceptable for supply air to a space. (a) Reprinted with permission from* Architectural Graphic Standards*, 11th ed.; © 2007 by John Wiley & Sons.; (b) Courtesy of Heat Pipe Technologies, Inc., and* Environmental Building News.

wheels prevent mixing of exhaust air and incoming air. A further precaution in the process purges each sector of the wheel briefly, using fresh air to blow away any unpleasant residual effects of the exhaust air on the wheel surfaces. Carryover of exhaust air qualities, except those of heat and moisture, is between 4% and 8% without purging and less than 1% with purging. Efficiency ranges from 70% to 80%, and available sizes range up to 144 in. (3.6 m) in diameter. Table 5.8, Part B, shows some representative sizes, airflows, and efficiencies. A smaller example of this device is shown in Fig. 5.17*c.*

(d) Desiccant Cooling

Another rotating-wheel process involves *desiccant cooling.* Desiccant cooling systems (Fig. 5.21) are attractive because they use no refrigerants (that may contain CFCs), and they lower humidity without overcooling the air. The desiccants (such as silica gel, activated alumina, or synthetic polymers) in an *active* system must be heated to drive out the moisture they remove from the incoming air; at present, natural gas is typically used, but solar energy is a promising substitute given its plentiful summer availability. Waste heat from other mechanical systems may also be used. In a *passive* desiccant system, heat from a building's exhaust air is enough to release and vent the moisture removed from incoming air.

Research on materials suitable for desiccant cooling and solar-driven regeneration should produce improvements in the types available as well as their performance. For an extended discussion of both solid- and liquid-based desiccant systems, see Grondzik (2007).

(e) Task Dehumidification and Humidification

Humidity affects comfort; for a sedentary person, a 30% RH change will produce about the same comfort sensation as a 2F° (1C°) change in temperature.

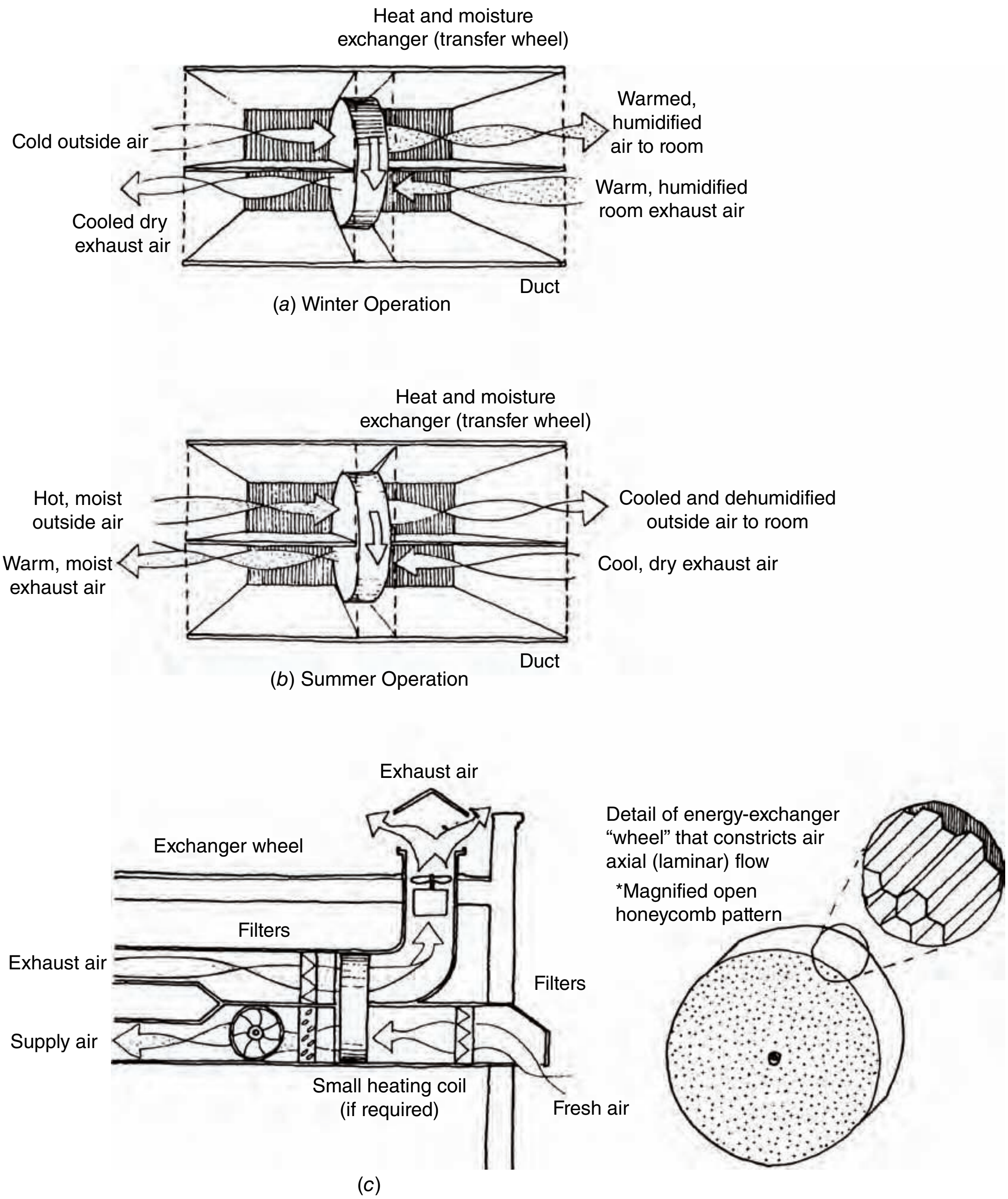
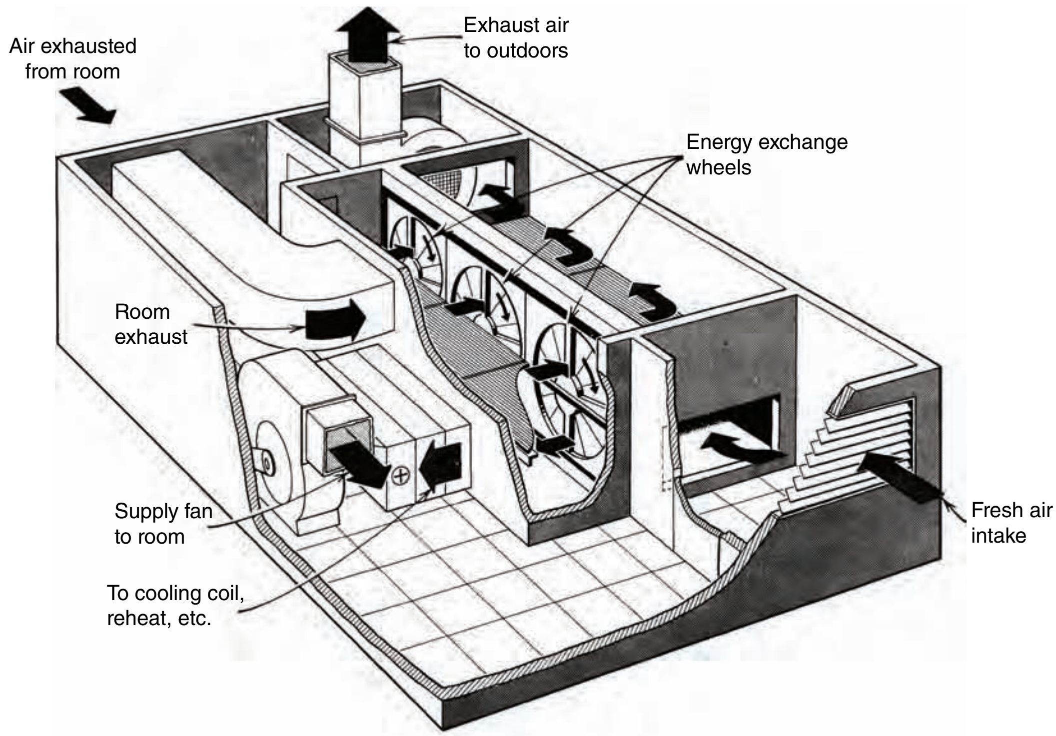
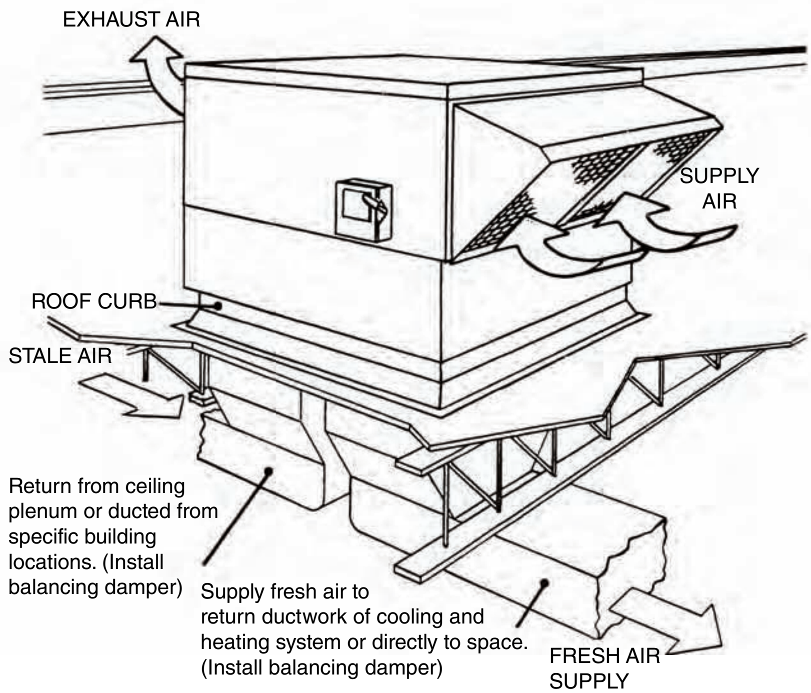


Fig. 5.20 *Energy transfer wheels. The wheel surface is impregnated with lithium chloride (or similar material), which absorbs moisture and transfers it to the other air stream. The wheel delivers moist air in winter (a) and dry air in summer (b). Cross section (c) through the wheel and the two air streams it serves. Exhaust air may be filtered to help keep the wheel clean. (d) Multiple-unit installation. Room exhaust air passes through the upper chambers, and incoming fresh air passes through the lower chambers. Wheels rotate at 8 to 10 rpm. (e) Rooftop unit supplies up to 1000 cfm (500 L/s). (Courtesy of Air Xchange, Inc., Rockland, MA.)*



(*d*)



(*e*)

Fig. 5.20 *(continued)*

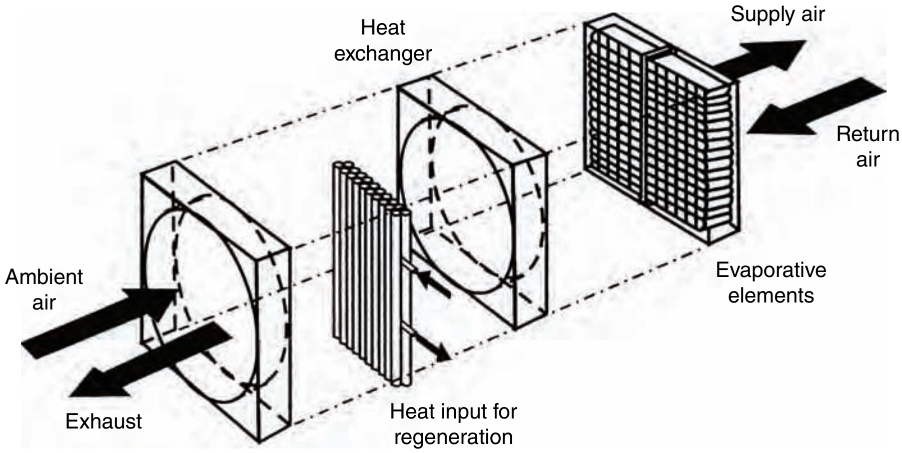
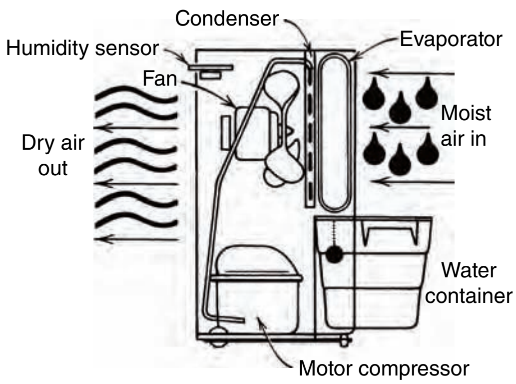


Fig. 5.21 *Desiccant cooling utilizes a rotating wheel impregnated with either silica gel or another desiccant material. The wheel removes moisture from incoming hot outdoor air and delivers some of it to outgoing exhaust air. The remaining moisture must be driven from the wheel by a heat source: natural gas or, ideally, solar energy. (National Renewable Energy Laboratory.)*

Higher humidity adds to hot air discomfort, making evaporation more difficult, increasing skin wettedness, and increasing the friction between skin and clothing or furniture surfaces. As RH exceeds 60%, problems with IAQ increase due to mold and mildew growth. Lower humidity produces cooler and drier sensations, but too-low humidity can irritate the skin.

For spaces that need only dehumidification rather than mechanical cooling, *refrigerant dehumidifiers* are commercially available (Fig. 5.22). Their advantage over desiccant dehumidifiers is that



Typical Performance Data

Watts	290	450	465	630
Pints per day[a]	14	20	25	30
Unit dimensions (in.)				
Height	20 1/2	20 1/2	21 1/2	21 1/2
Width, 11 3/4				
Depth, 16 3/4				
"Average" room size served	20′ × 32′	35′ × 40′	40′ × 48′	40′ × 60′

[a]For air at 80°F, 60% RH.

Fig. 5.22 *Refrigerant dehumidifiers typically are installed as free-standing units in smaller buildings.*

the air temperature remains essentially unchanged during dehumidification (desiccant dehumidifiers raise the temperature of the dried air). These devices consume energy to run the refrigeration cycle, however, and this energy is added, as heat, to the space. Accumulated water must periodically be removed from these units and, if untended, could become a source of disease. Most refrigerant dehumidifiers encounter operating difficulties at air temperatures below 65°F (18°C), at which point frost forms on their cooling coils. This could cause problems in a tightly enclosed residence in winter.

Task *humidifiers* are widely available and often used to relieve symptoms of respiratory illnesses. Again, the problem of bacterial and mold growth in water reservoirs arises; some products add an ultraviolet (UV) lamp to counteract this threat.

(f) Filters

There is a wide variety of particle air pollutants, as described in Table 5.2. The larger particulates are the easiest to remove, but much smaller respirable particles pose a greater threat to health. Not all pollutants can be removed by filters. Figure 5.23 compares filter groups and testing methods with associated filter efficiencies. Groups I, II, and III are widely used and are generally illustrated in

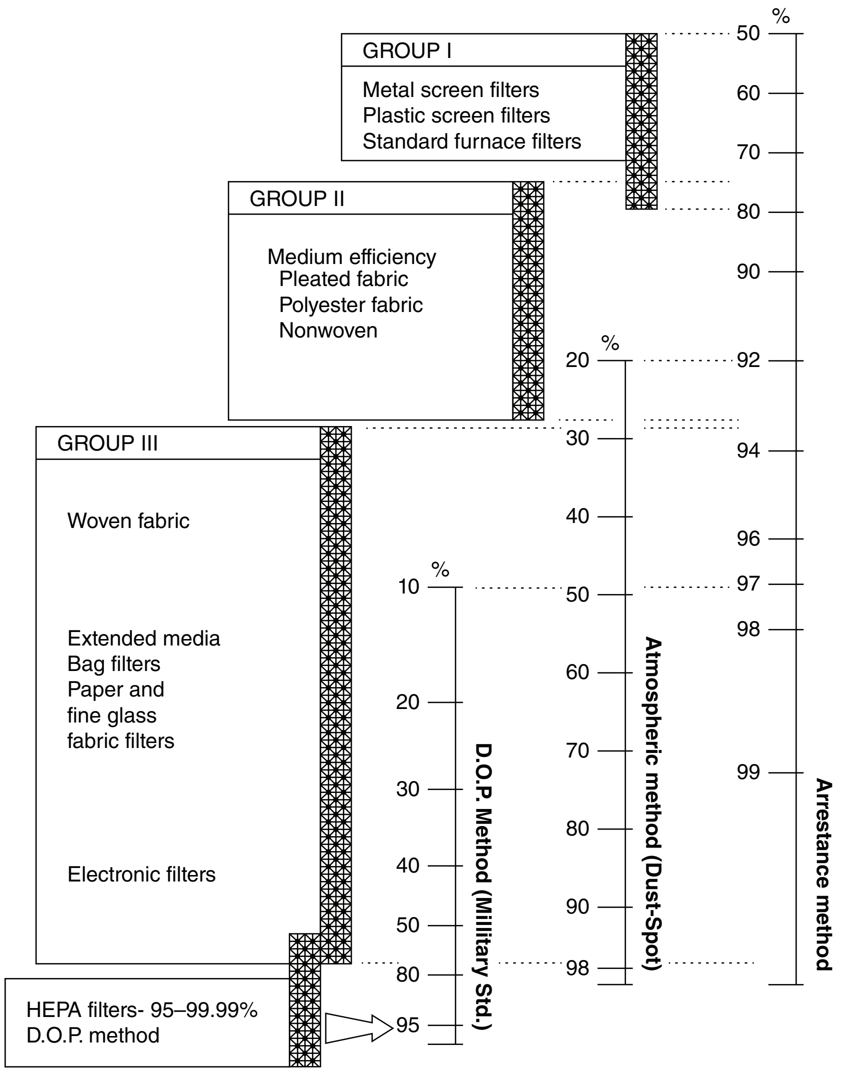


Fig. 5.23 *Air filter efficiencies. Methods of determining efficiency vary; the Arrestance Method can be used across all groups, while the Atmospheric (Dust-Spot) Method should be used for medium- and high-performance filters. The Detection Operational Program (DOP) Method is a military standard. (From D. Rousseau and J. Wasley. 1997.* Healthy by Design. *Hartley & Marks. Point Roberts, WA.)*

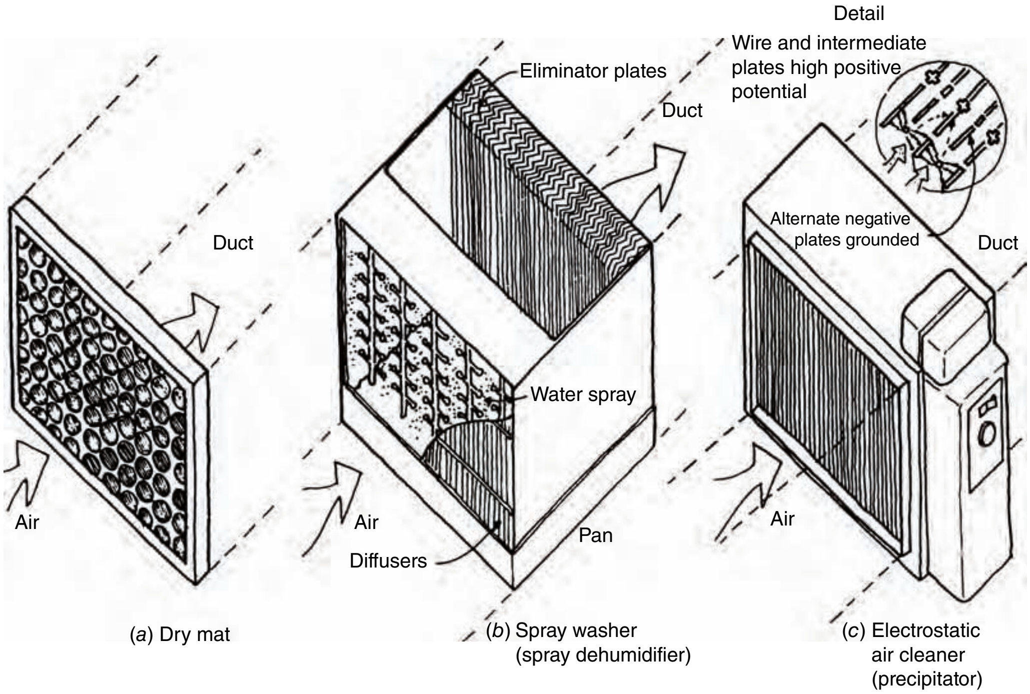


Fig. 5.24 *Several air filter types (a, b, c); not shown are pleated and roll types.*

Fig. 5.24. The highest-efficiency filter, the high-efficiency particulate arrestance (HEPA), is most often found in special air cleaners for unusually polluted or IAQ-demanding environments. Air filter characteristics are summarized in Table 5.9.

ANSI/ASHRAE Standard 52.2-2012, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, is a newly revised filtration standard that combines two former standards into one, to offer a test procedure for

TABLE 5.9 Air Filter Characteristics

	Percent Efficiency Range			
Media and Type	**Atmospheric Dust**	**Small Particles**	**Dust-Holding Capacity**	**Airflow Resistance in. water (Pa)[a]**
Dry panel, throwaway	15–30	NA	Excellent	0.1–0.5 (25–125)
Viscous panel, throwaway	20–35	NA	Good	0.1–0.5 (25–125)
Dry panel, cleanable	15–20	NA	Superior	0.08–0.5 (20–125)
Viscous panel, cleanable	15–25	NA	Superior	0.08–0.5 (20–125)
Mat panel, renewable	10–90	0–60	Good to superior	0.15–1.0 (37–250)
Roll mat, renewable	10–90	0–55	Good to superior	0.15–0.65 (37–162)
Roll oil bath	15–25	NA	Superior	0.3–0.5 (75–125)
Close pleat mat panel	NA	85–95	Varies	0.4–1.0 (100–250)
High-efficiency particulate	NA	95–99.9	Varies	1.0–3.0 (250–745)
Membrane	NA	to 100	NA	NA
Electrostatic with mat	80–98	NA	Varies	0.15–1.25 (37–310)

Source: Reprinted by permission from AIA: Ramsey and Sleeper, *Architectural Graphic Standards*, 10th ed., © 2000 by John Wiley & Sons.

[a]Higher airflow resistance values will require increased fan energy.

evaluating the performance of air-cleaning devices as a function of particle size. The standard addresses three air-cleaner performance characteristics: (a) ability of the air cleaner to remove particles from the air, (b) total dust-holding capacity with arrestance (weight efficiency), and (c) the device's resistance to airflow.

Particulate Filters. Particulate filters are very common and come in several guises. Panel filters are furnished with HVAC equipment and function mainly to protect the fans from large particles of lint or dust. Because panel filters are relatively crude, they are not really considered to be air-cleaning equipment. Media filters are much finer, using highly efficient pleated filter paper within a frame. They function both by straining and impaction. The larger particles are strained out by the closely spaced filter fibers, while some of the smaller particles that would otherwise pass through are pushed into the fibers by air turbulence. Particulate filters need regular maintenance, especially media filters, which can become blocked and cause damage to HVAC equipment and increased energy consumption if not replaced frequently enough. Media filters of high quality are expected to perform at an efficiency of 90% (minimum) and are typically at least 6 in. (150 mm) deep; this is for a six-month minimum life cycle.

Adsorption Filters. Adsorption filters are for gaseous contaminant removal and vary according to the pollutant in question. Activated-charcoal filters are the most common of these types, absorbing materials with high molecular weights but allowing those of lower weights to pass. Other adsorption filters use porous pellets impregnated with active chemicals such as potassium permanganate; the chemicals react with contaminants, reducing their harmful effects. Adsorption filters must be regularly regenerated or replaced.

High-quality adsorption filters contain gas adsorbers and/or oxidizers with sufficient capacity to remain active over a full service cycle of 6 months at 24 hours per day, 7 days per week. Air velocity should be such as to allow the air to remain in the filter for about 0.06 second.

Air Washers. Air washers are sometimes used to control humidity and bacterial growth. The moisture involved can pose a threat if these devices are not well maintained.

Electronic Air Cleaners. Electronic air cleaners can pose a different threat due to ozone production, but have the advantage of demanding less maintenance. Static electricity is produced in the self-charging mechanical filter by air rushing through it; larger particles thus cling to the filter. The more humid the air and/or higher the air velocity, the lower the filtering efficiency. In a charged media filter, an electrostatic field is created by applying a high DC voltage to the dielectric material of the filter. Many particles are not polarized, however, due to the weakness of the field. A two-stage electronic air cleaner first passes dirty air between ionizing wires of a high-voltage power supply. Electrons are stripped from the particulate contaminants, leaving them positively charged. Then these ionized particles pass between collector plates that are closely spaced and oppositely charged. The particles are simultaneously repelled by the positive plates and attracted to the negative plates, where they are collected.

(g) Locating Air-Cleaning Equipment

Before the advent of IAQ concerns, buildings were often designed with rather crude panel filters located only at the HVAC equipment; they were primarily intended to intercept materials that might adversely affect combustion or heat exchange. In addition to these equipment-protecting devices, a building requiring high IAQ will now have a combination of high-efficiency particle filters and adsorption filters.

The panel filters provided with HVAC equipment are usually located *upstream* from the unit fan. High-efficiency particle and adsorption filtering systems should be located *downstream* from the HVAC cooling coils and drain pans to ensure that any microbiological contaminants from those wet surfaces are removed rather than being distributed throughout the building.

In buildings where a filtering system must be integrated with a central HVAC system (typical of small buildings), the HVAC system should be capable of continuously circulating air at the rate of 6 to 10 times per hour and of operating against the considerable static pressure that results from high-efficiency filters.

Fig. 5.25 *A stand-alone electrostatic air filter operates independently of the central HVAC system; no ductwork is required. Airflow rates vary; the slower the flow, the more efficient the filtering. Flush-mount (recessed in suspended ceiling), ceiling surface–mount, wall-mount, and portable models are available.(Courtesy of Tectronic Products Co. Inc., East Syracuse, NY.)*

(h) Ultraviolet Radiation (UV)

Since early in the twentieth century, UV radiation in the C band (200–280 nm wavelength) has been used to kill harmful microorganisms, but under tightly controlled conditions. Now there are UV lamp units that work within HVAC systems, promising to control fungi, prevent the development and spread of bacteria, and reduce the spread of viruses. As an additional benefit, cooling coils and drain pans stay cleaner. The germicidal output of these lamps is somewhat higher at room temperatures (and above) than at lower temperatures. These devices take up very little space (they are placed within ductwork) and generate no ozone or other chemicals. They are even more effective when installed in a UV-reflective duct interior: Aluminum seems to be the best UV reflector commonly available. UV lamp life is 5000 to 7500 hours.

UV radiation also looks promising as a treatment for VOCs. The National Renewable Energy Laboratory is helping to develop a process that bombards polluted air with UV radiation in the presence of special catalysts. Pollutants including cigarette smoke, formaldehyde, and toluene are quickly broken down into molecules of water and carbon dioxide.

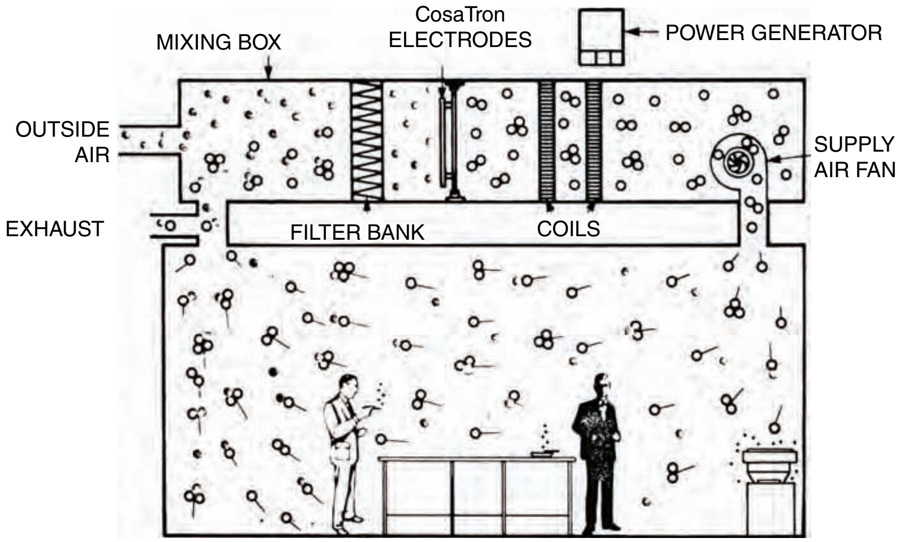
(i) Individual Space Air Cleansing

Energy conservation considerations have reduced the air circulation rate in many central air-handling systems; moving less air reduces the energy used by fans. One result can be low distribution efficiency, which causes poorly mixed air within the occupied spaces. With local (individual space) air-filtering equipment, both a high circulation rate and proper air mixing are achievable. Each such unit has its own fan that can operate either with or without the central HVAC fan. An example of an independent electrostatic air filter is shown in Fig. 5.25.

Air circulation through these filters should occur at rates between 6 and 10 air changes per hour. The air is then ducted to diffusers, hence circulating in a sweeping pattern across a space to return air intakes on the opposite side.

A variation on electrostatic air cleaning is shown in Fig. 5.26. In this equipment, a mixture of outdoor and indoor air is passed through a complex electrical field produced by both high-voltage DC and high-frequency AC. This supply air emerges with greatly reduced submicron particles that have coagulated into larger particles more easily carried by air currents. As this air moves through the occupied space, it picks up submicron particles and is returned to the equipment (some is exhausted), where it is filtered to remove the larger particles.

Portable air cleaners abound. One elaborate model combines UV germicidal radiation with carbon/oxidizing media and HEPA. It is a counter-height rolling device about 15 in. (380 mm) square that emits cleansed air from the top. It claims to purify air in a space of about 12,000 ft^3 (340 m^3).



Interactive Animation

Fig. 5.26 *This air-cleaning system uses a combination of high-voltage DC and high-frequency AC. The supply air emerges with greatly reduced submicron particles, which have coagulated into larger particles more easily carried by air currents. As this air moves through the occupied space, it picks up submicron particles and is either exhausted or returned to the equipment, where it is filtered to remove the larger particles. (Courtesy of CRS Industries Inc., Tampa, FL.)*

(j) Controls for IAQ

A large number of air quality–monitoring devices are now available, some of which can control the operation of IAQ-related equipment. One of the oldest and simplest devices measures the concentration of CO_2 in parts per million (ppm). Wherever there are indoor concentrations of people, elevated levels of CO_2 can be expected. Thus, CO_2 becomes a kind of "canary in the coal mine," an early indicator of pollutant buildups due to occupancy. In the Bedales School theater (Fig. 5.9), the operation of the exhaust air dampers in the cupola is controlled by a building management system. Under ordinary conditions, damper opening is regulated by information from the CO_2 monitor. This can be overridden by indoor and outdoor temperatures (summer night ventilation is encouraged), air velocity monitors below the seats (too much draft could produce discomfort), the presence of wind and rain (openings limited), or a fire alarm (damper fully open to aid in smoke extraction).

Where contaminants are expected from both sources and human beings (typically the case), monitors may be installed to detect carbon monoxide, or combinations of VOCs, or fuels such as propane, butane, or natural gas—or even depletion of oxygen. These monitors can be installed as standalone alarms or with additional relays that activate equipment. They are about the size of a programmable thermostat; the mounting height depends upon which gas is to be monitored.

Such devices can regulate ventilating heat exchangers, such as the ERV (shown in Fig. 5.18). This could be especially useful during unoccupied periods, holidays, and weekends. Many HVAC systems are shut off during such extended periods; VOCs from finishes and furnishings continue to accumulate, however. Periodic flushing from ERVs, controlled by VOC monitors, will help maintain acceptable air quality and could eliminate (or greatly reduce) the need for a Monday morning preflush.

5.7 IAQ, MATERIALS, AND HEALTH

The effect of IAQ on occupant health and productivity is an emerging building design issue. This concern stems partly from increasing interest in green design (with its focus upon environmental quality and the resulting impact on materials choices) and partly from continuing stories about the adverse health impacts of poor IAQ (especially cases involving mold and mildew).

(a) Multiple Chemical Sensitivity

This is an unusual (and sometimes controversial) condition, also known as *environmental illness*. The controversy arises because the causes of this condition are poorly understood and likely involve numerous factors. When causes are mysterious, establishing targeted remedies becomes difficult. People with multiple chemical sensitivity are likely to see the provision of outstanding IAQ as a primary intent of the design process. People with this condition avoid environments with any known environmental risk factors.

Ecology House (in San Rafael, California) is an apartment complex for people with multiple chemical sensitivity. Its construction avoided plywood, using Douglas fir sheathing instead; the floors are tile instead of wall-to-wall carpet; cabinets are metal, not plywood or oriented strand board; the heating system is radiant hot water, not forced air. Barbecues and fireplaces are absent, painted surfaces are minimized, and any window coverings are alternatives to curtains. There is even an "airing room" where, for example, newspapers can be hung before they are read in order to evaporate ink odors.

(b) Materials and IAQ

There is a rapidly growing availability of environmentally responsible building materials. Many such products address the issue of outgassing via low-VOC formulations. Others provide alternative materials to replace less-benign products in common use. Even so, quantitative data are hard to find. Manufacturers of building materials are required to provide Material Safety Data Sheets (MSDS). These reports list all chemical constituents that make up at least 1% of a material (and are not deemed proprietary). Unfortunately, this information does not predict pollutant emission rates. A designer is left with the suspicion that the higher the percentage content of a chemical, the more likely its outgassing.

(c) Green Design and IAQ

Several key organizations—American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the American Institute of Architects (AIA), Building Owners and Managers Association (BOMA), Sheet Metal and Air-Conditioning Contractors' National Association (SMACNA), the U.S. Environmental Protection Agency, and the U.S. Green Building Council—have worked collaboratively to offer guidance, both general and specific, for indoor air quality in buildings during the design, construction, and commissioning processes (Indoor Air Quality Guide, 2009).

The U.S. Green Building Council's LEED rating system has helped to improve the visibility of acceptable IAQ as a design objective. LEED for new construction and major renovations, for example, establishes compliance with ASHRAE Standard 62 and control of tobacco smoke as prerequisites for LEED certification. Beyond these minimums, designers may choose to address CO_2 monitoring, low-emitting materials, or pollutant source control strategies (among others) to achieve rating points. See Appendix H.3 for further information.

References and Resources

AIA. 2000. Ramsey, C. G. and H. R.Sleeper. *Architectural Graphic Standards*, 10th ed. American Institute of Architects/John Wiley & Sons. New York.

AIA. 2007. Ramsey, C. G. and H. R.Sleeper. *Architectural Graphic Standards*, 11th ed. American Institute of Architects/John Wiley & Sons. Hoboken, NJ.

ASHRAE. 2009. *Indoor Air Quality Guide, Best Practices for Design, Construction, and Commissioning*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA. (Developed by ASHRAE, AIA, BOMA, SMACNA, USEPA, USGBC.)

ASHRAE. 2012. ANSI/ASHRAE Standard 52.2-2012, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2013. ANSI/ASHRAE Standard 62.1-2013, *Ventilation for Acceptable Indoor Air Quality.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2013. ANSI/ASHRAE Standard 62.2-2013, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Banham, R. 1969. *The Architecture of the Well-Tempered Environment*. University of Chicago

Press, Chicago, and the Architectural Press, London.

Chandra, S., P. W. Fairey, and M. Houston. 1986. *Cooling with Ventilation*. Solar Energy Research Institute. Golden, CO.

Fanger, P. O. 1989. "The New Comfort Equation for Indoor Air Quality." *ASHRAE Journal*, October 1989.

Grondzik, Walter T. 2007. *Air-Conditioning System Design Manual*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Hellmuth, Obata and Kassabaum. 2001. EPA 220/K-02-001, *The Greening Curve: Lessons Learned in the Design of the New EPA Campus.* U.S. Environmental Protection Agency. Washington, DC.

The New Buildings Institute. http://www.newbuildings.org/

NREL. April 1988. *Federal Technology Alert: Transpired Collectors (Solar Preheaters for Outdoor Ventilation Air).* National Renewable Energy Laboratory, U.S. Department of Energy. Boulder, CO.

Rousseau, D. and J. Wasley. 1997. *Healthy by Design*. Hartley and Marks. Point Roberts, WA.

Shurcliff, W. A. 1981. *Air-to-Air Heat Exchangers for Houses*. Brick House. Andover, MA.

U.S. Environmental Protection Agency, Research Triangle Park Campus: http://femp.buildinggreen.com/overview.cfm?ProjectID=30

U.S. Environmental Protection Agency, Indoor Environments Division (IAQ): http://www.epa.gov/iaq/

CHAPTER 6

Solar Geometry and Shading Devices

AN UNDERSTANDING OF THE SUN'S POSITION DURING the day is critical to site planning, daylighting design, passive solar design, and controlling unwanted heat gains. In early civilizations, most cultures revered the sun as a deity and understood its patterns and importance in the cycle of life. Today, such understanding is just as important when considering the relationships between the environment and technology in the design of buildings. We can no longer afford the resources to sustain the construction and operation of buildings with poorly designed glazed areas habitable only through the use of active climate control systems. We can rely on the patterns of the sun as a constant in the design process and create environments that work with these patterns, climate, and well-considered design intents.

6.1 THE SUN AND ITS POSITION

The sun is a giant star and the largest object in the solar system. The sun's energy is produced by nuclear fusion that occurs at temperatures in the range of 18–25 million °F (10–14 million °C). The energy from thermonuclear fusions at the sun's surface is released as electromagnetic radiation at approximately 10 million °F (5.6 million °C). The solar spectrum (Fig. 6.1) consists of approximately 5% ultraviolet (shortwave) radiation (less than 350 nm), 46% light—what we see—(350 to 750 nm), and 49% infrared (longwave) radiation (greater than 750 nm). Though 93 million miles from Earth, the amount of the sun's radiation (heat energy) reaching the Earth's outer atmosphere is relatively stable and is called the *solar constant*—433 Btu/ft^2 hr (1.37 kW/m^2). Some annual variation in the solar constant occurs because of the elliptical orbit of

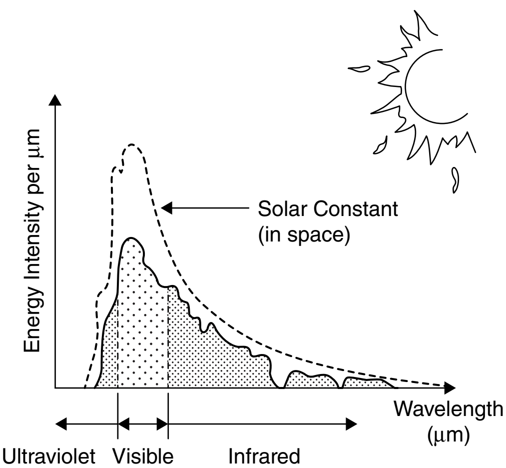


Fig. 6.1 *At the Earth's surface the solar radiation spectrum consists of ultraviolet radiation, visible radiation (light), and infrared radiation. (Drawing by Erik Winter; © 2004 Alison Kwok; all rights reserved.)*

the Earth around the sun, but it is so small that it has little effect on building design. The length of the radiation's path through the atmosphere is the most important factor in determining how much radiation reaches the surface of the Earth. This received radiation is termed *insolation.*

(a) Earth's Rotation and Tilt

The Earth's axis of rotation is tilted at 23.5° (precisely, 23.47°), also known as its *declination*. The Earth travels in the plane of the ecliptic (Fig. 6.2) in its orbit around the sun. The tilt of the Earth is toward the sun (June +23.5°) or away from the sun (December −23.5°). This tilt is responsible for the seasons. In the northern hemisphere in June, the sun's direct radiation is perpendicular to the Earth's surface; in December, there are fewer hours of sun, and the radiation passes through a longer, nonperpendicular, length of atmosphere to reach the Earth. The rotation of the Earth (once every 24 hours) and its tilt determine the length of atmosphere that solar radiation passes through, and consequently how much energy the Earth's surface receives.

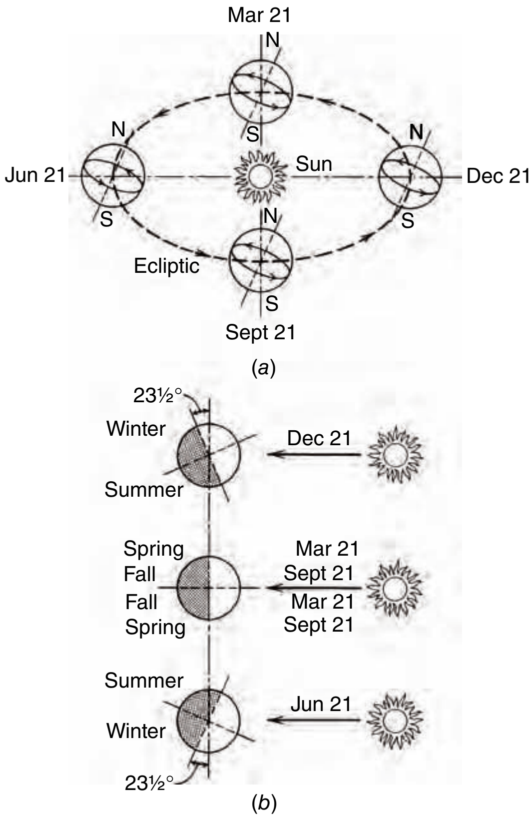


Fig. 6.2 *(a) The ecliptic is the annual path of the Earth around the sun. (b) The tilt of the Earth's axis in the plane of the ecliptic results in the seasonal variations. In the northern hemisphere the Earth tilts away from the sun in December (–23.5°), resulting in winter's low sun altitude and cold weather. In June the effect is reversed.*

(b) Altitude and Azimuth

The position of the sun at any instant with respect to an observer on the ground is defined by its *altitude angle* and its *azimuth angle*. The *altitude* of the sun is the angle between the horizon and the sun's position above the horizon. The altitude varies during the day, beginning and ending at 0° at sunrise and sunset and reaching a daily maximum at *solar* noon. The altitude angle at noon varies from day to day, reaching a yearly maximum on June 21 (the summer solstice), a minimum on December 21 (the winter solstice), and a point halfway between the two on the vernal and autumnal equinoxes (March 21 and September 21). The *azimuth* (also called the solar bearing angle) is the angle along the horizon between the projected position of the sun and true (solar) south. Note that the azimuth is referenced from south herein, whereas in other sources it is sometimes referenced from north; there is no clear consensus on this issue. Refer to Fig. 6.3 and Tables C.11 to C.18 for solar position and insolation information.

Referring to the graphic relationships in Fig. 6.2, the height of the sun in the sky (altitude angle) depends upon the observer's position on the

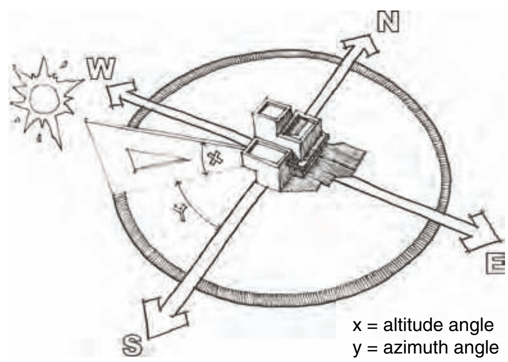


Fig. 6.3 *Altitude and azimuth angles. (Drawing by Erik Winter; © 2004 Alison Kwok; all rights reserved.)*

Earth (the latitude) and the seasonal changes (the tilt of the Earth). This can be expressed in Equation 6.1, as follows:

$$\text{altitude angle at solar noon} = 90° - \text{latitude} \pm \text{declination} \quad (6.1)$$

For example, the solar altitude for Minneapolis (44.9°N) for various seasons at solar noon is:

Maximum (June 21): = 90° – ~45° + 23.5° = 68.5°

Equinox (Mar/Sept 21) = 90° – ~45° – 0° = 45°

Minimum (Dec 21) = 90° – ~45° – 23.5° = 21.5°

These relations are shown graphically in Fig. 6.4.

The azimuth angle during its path from sunrise to sunset changes with the season. On

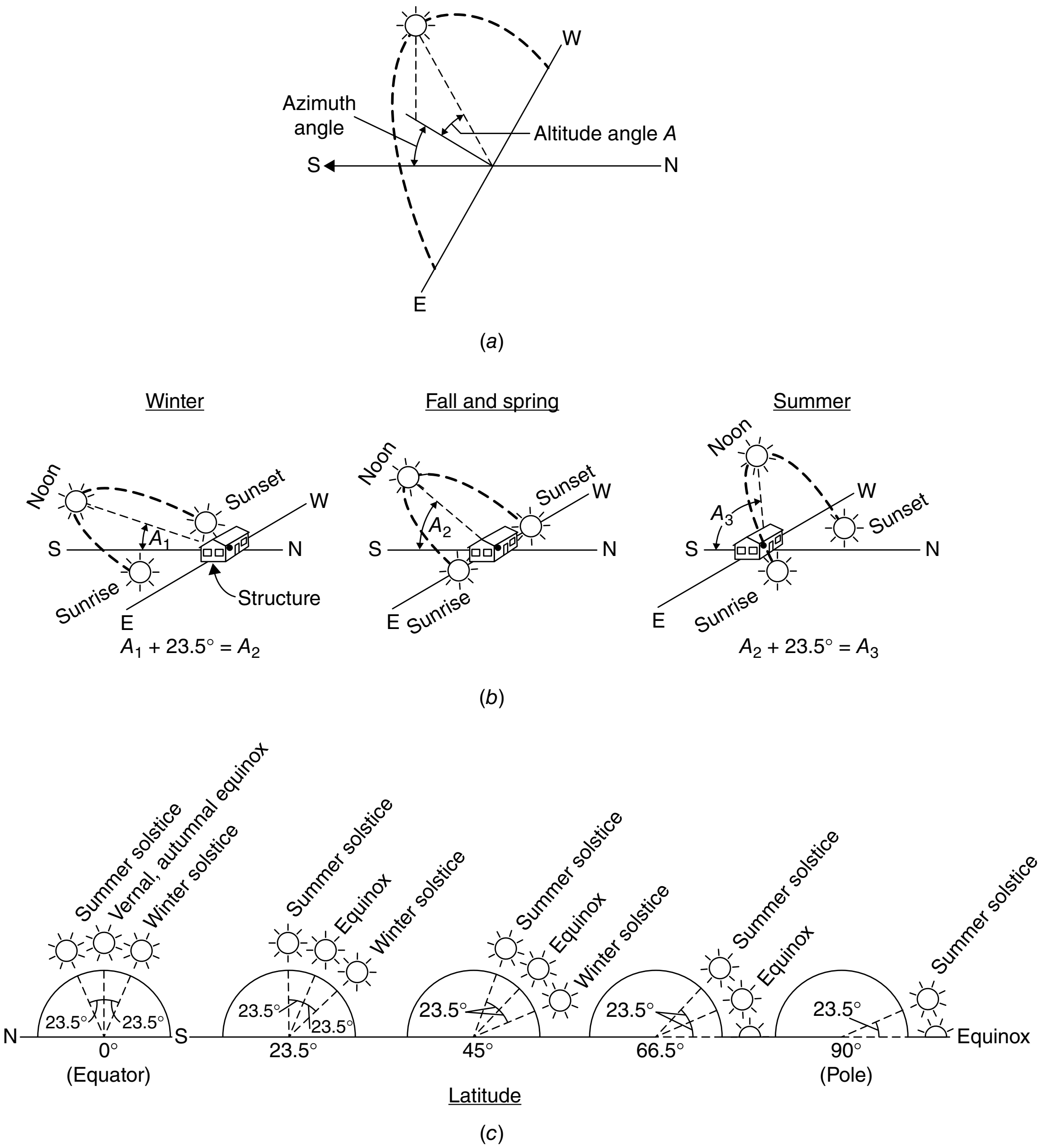


Fig. 6.4 *(a) The position of the sun is expressed in terms of vertical angle above the horizon (altitude) and horizontal angle (azimuth, measured from the south). (b) Approximate position of the sun in each of the seasons at a mid-northern latitude (approximately 45°). Note that the altitude angle is maximum in summer, minimum in winter, and in between in spring and fall. (c) Maximum sun altitude at various latitudes for both solstices and equinoxes.*

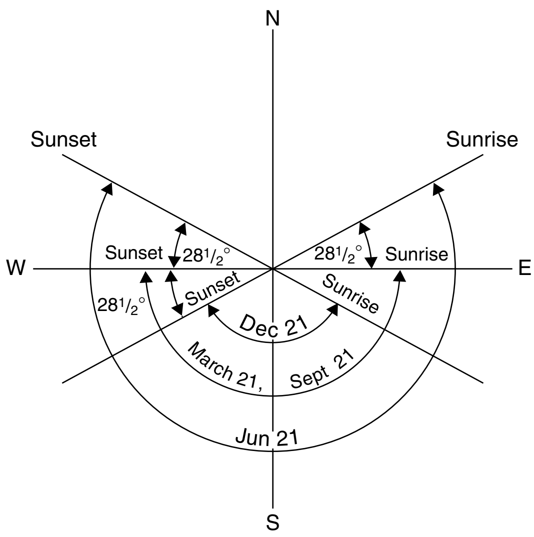


Fig. 6.5 *A diagram of the sun's azimuth path from sunrise to sunset projected on a horizontal plane for solstices and equinoxes at latitude 32°N (Jerusalem, Savannah, Tucson). The sun's azimuth angle, like its altitude, varies with the time of day and the date.*

the equinoxes (March 21 and September 21) the sun rises due east and sets due west. In the northern hemisphere, the sun rises north of east and sets north of west between March 22 and September 20. This is shown graphically in Fig. 6.5 for one specific latitude (32°N). Sunrise on June 21 is 28.5° north of east, and sunset is correspondingly 28.5° north of west. On December 21 sunrise and sunset are 28.5° south of east and west.

A designer can use three basic solar pattern concepts when designing with the sun:

1. The altitude of the sun is highest in summer, lowest in winter, and in between in spring and fall for all latitudes. The maximum difference in altitude angle between summer and winter solstices is about 47°.
2. The daily maximum altitude of the sun increases as a location approaches the equator (low latitudes, either north or south). The seasonal altitude *variation*, however, is the same for all latitudes (except at those extreme north and south latitudes where the sun is above or below the horizon for extended time periods). This factor not only has a pronounced effect on the design and efficacy of sunshading devices, but also affects exterior daylight illuminance levels.
3. The azimuth angle of the sun is dictated by the time of day and by the season. The sun by definition traverses the sky between sunrise and sunset and in the northern hemisphere rises north of east during the summer, due east on the equinoxes, and south of east during the winter. The principal significance of the azimuth angle is its role as an important consideration when orienting a building on a site, establishing building exposures, and analyzing shading angles.

6.2 SOLAR VERSUS CLOCK TIME

The basis of all timekeeping is the length of the solar day, that is, one full rotation of the Earth on its axis. The Earth's motion on the ecliptic is not uniform—it moves more rapidly when farther from the sun. As a result, the actual length of a solar day varies. Since it is impractical to use timepieces that need daily adjustment, we use an average, or *mean solar day*, as the basis for timekeeping. There are three reasons for the difference between solar time and clock time:

1. *Location within a time zone.* The 360° circumference of the Earth is divided into 24 one-hour time zones, each with a width of approximately 15° of longitude, which corresponds to approximately 1000 miles (1610 km). An observer located at any point other than directly on a standard time zone reference longitude (normally in the center of a time zone) must make a time correction for his/her distance from the reference longitude. (In some countries, a reference longitude is more than 30 minutes from time zone extremes. In such places, the time correction for longitude plus the equation of time can total well over an hour. This situation does not exist in the continental United States.)
2. *Equation of time.* The speed of the Earth in its orbit around the sun is nonuniform; the planet moves less rapidly when farther from the sun. As a result, the actual length of the solar day varies as defined by the *equation of*

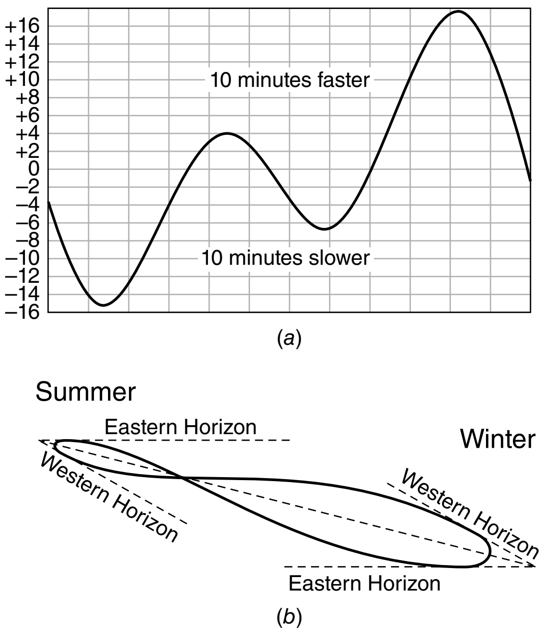


Fig. 6.6 *(a) Equation of time. (b) The analemma is a miniature almanac where the vertical coordinates of the path represent the sun's declination on a particular day of the year, while the horizontal coordinates tell how much the sun is ahead of or behind clock time on that day. (Drawings by Erik Winter; © 2004 Alison Kwok; all rights reserved.)*

time (Fig. 6.6*a*). The extent of this variation can be determined from a curve called the *analemma* (Fig. 6.6*b*) or from tabulations in various sources. The analemma is the shape that results if the sun's position in the sky is recorded at the same time of day throughout the year.

3. *Daylight saving time (DST).* During DST, clocks are moved forward one hour to effectively give (from the morning) one more hour of daylight in the evening during the summer months. (Note: The official term is daylight saving time, not daylight savings time.) The purpose of DST is to make better use of daylight. In most of the United States (except Arizona and Hawaii), DST begins at 2:00 A.M. on the second Sunday of March and reverts back to standard time on the first Sunday in November. In the European Union, Summer Time begins at 1:00 A.M. Universal Time (Greenwich Mean Time) on the last Sunday in March and ends the last Sunday in October.

Unless otherwise clearly noted, most solar position tables and charts (including sunpath diagrams) are based upon solar time, not clock time. This must be considered when solar-driven loads are being added to clock-driven loads (for example, the heat gain from the western sun is being added to the heat gain from office occupants to determine the total load). Such an addition must use coincident values, and solar and clock times are rarely coincident.

6.3 TRUE SOUTH AND MAGNETIC DEVIATION

Working from a "true south" or "solar south" orientation (opposite of "true north," location of the Earth's axis of rotation) is the starting point in the planning and design of a building, particularly for passive solar strategies. When a compass is used on a building site to find north, the compass yields a reading toward magnetic north, determined by the Earth's internal magnetic field. This is usually (depending upon the locale) not the same as true north. Figure 6.7 illustrates this phenomenon. To correct between magnetic north (compass) and true north (solar), a magnetic deviation is applied to the compass reading. Depending upon the location on the Earth's surface, the deviation may be as large as 50°—but in most locations this is not the case. It should be noted that the magnetic field is not uniform, stationary, or perfectly aligned with the Earth's poles; thus, magnetic deviations can change and have changed over time.

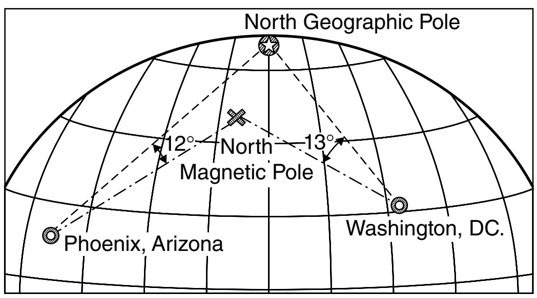


Fig. 6.7 *The concept of magnetic deviation (from true north), illustrated for Phoenix, Arizona (12° easterly) and Washington, DC (13° westerly). (Drawing by Erik Winter; © 2004 Walter Grondzik; all rights reserved.)*

6.4 SUNPATH PROJECTIONS

Design tools such as sunpath projection charts can be used to assess site conditions, orient a building, or provide information critical for passive solar design. Sunpath charts represent the sun's position throughout the year. There are two fundamental types of sunpath projections: vertical and horizontal. Horizontal projections are more commonly encountered. The basic idea behind the horizontal projection is shown in Fig. 6.8. The sky vault is represented as a hemisphere that projects as a circle, the center of which is the zenith. The observer looks down onto the hemispherical sky vault and

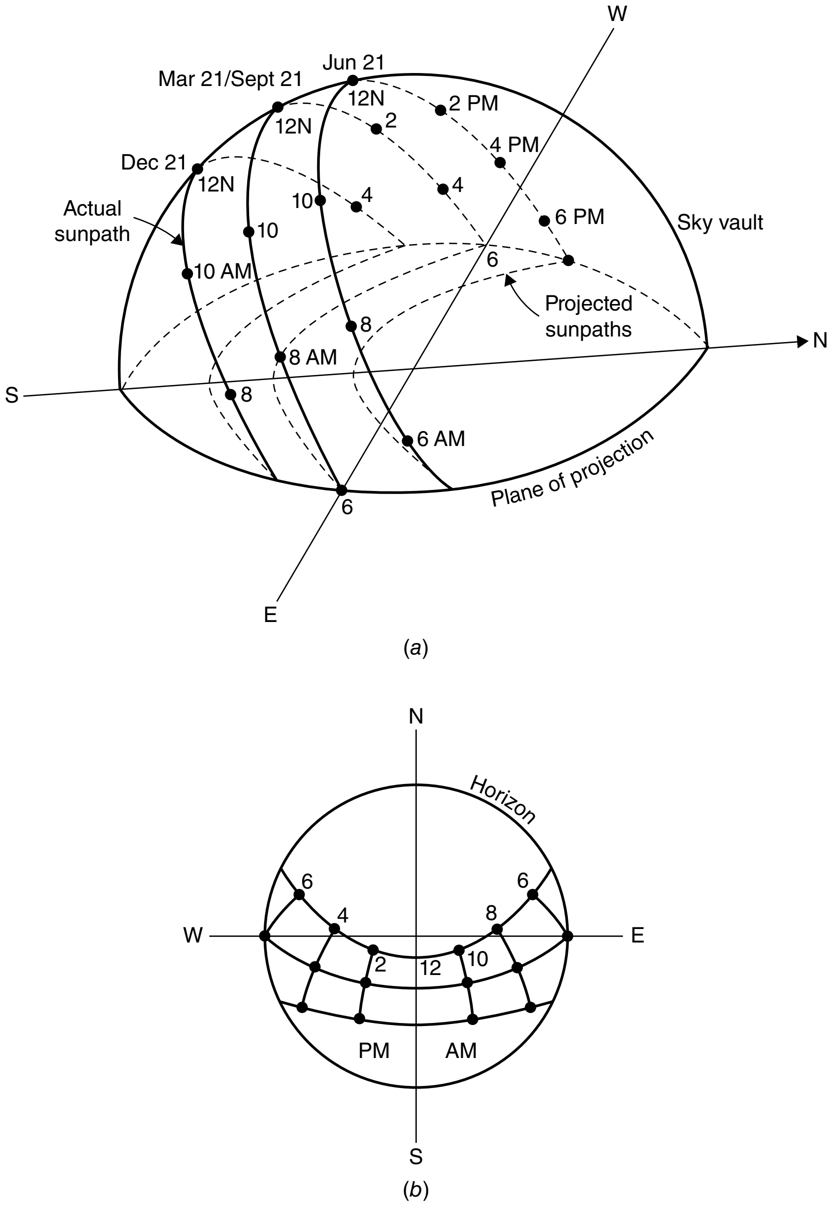


Fig. 6.8 (a) The sky vault is represented as a hemisphere, which projects as a circle (b) on a projection plane. The exact shape of the sunpath chart depends upon the projection method. The hour points on the sunpath chart are connected to form hour lines that are useful for interpolation.

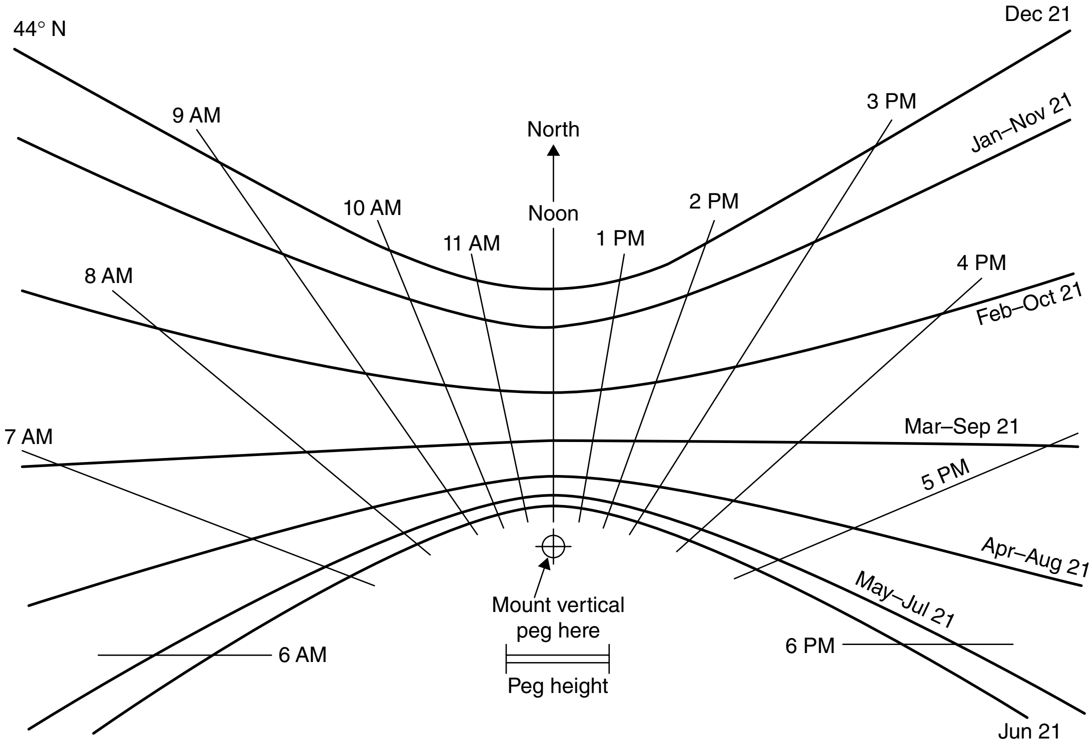


Fig. 6.9 *Sunpeg chart for 44°N latitude.*

projects the sunpaths from the vault onto the two-dimensional projected circle. The basic difference between the various horizontal projections is in the spacing between circles of equal altitude. Vertical projection charts are also available.

Four of the more common sunpath projections are: (1) gnomonic, (2) equidistant, (3) rectilinear, and (4) stereographic.

1. The *gnomonic projection* (used with sundials and sunpeg charts) is derived from the sundial. The observer is at the center of the projection; therefore, low sun angles (sunrise, sunset) extend to infinity. For this reason, this method is rarely used for solar charts but is easily applied to building shadow studies. Sunpeg charts for specific latitudes (see Fig. 6.9 and Appendix D.2) will show the exact position of sun penetration and shadow on a model of any scale, on any date, at any time of day between shortly after sunrise and shortly before sunset. Use of the sunpeg chart is explained in the following outline (reprinted by permission from Brown, Reynolds, and Ubbelohde, *Inside Out: Design Procedures for Passive Environmental Technologies*, John Wiley & Sons, © 1982) and shown in Fig. 6.10.

- *Find the sunpeg chart corresponding to the nearest latitude for a site.*

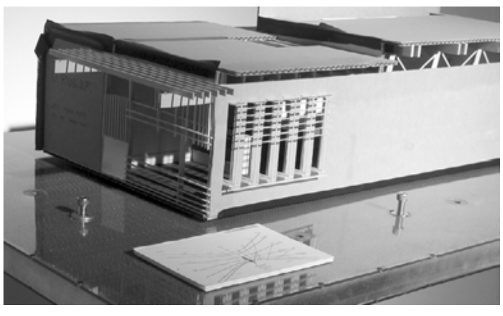
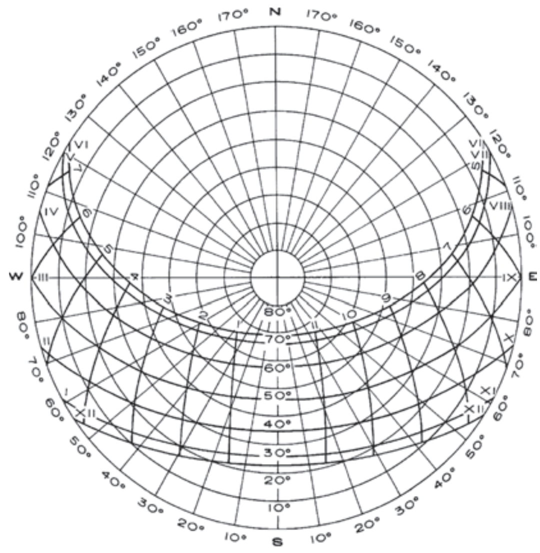


Fig. 6.10 *A sunpeg chart attached to the base of a scale model to study solar access and shadow patterns in and about a building. (Photo by Jonathan Meendering; © 2004 Alison Kwok; all rights reserved.)*

- *Make a copy of this chart. If the copier changes the chart size, the peg height line will also change; there should be no problem.*
- *Construct a "peg" (gnomon) whose finished height above the chart surface corresponds exactly to the "peg height" shown on the copy of the chart. This peg must stand and remain perfectly vertical relative to the model and not be bumped out of vertical alignment.*
- *Mount the copy of the chart on the model to be tested. The chart must be perfectly horizontal over its entire surface, and the north arrow on the chart must correspond to true (solar) north on the model.*
- *Choose a test time and date. Take the model out into direct sunlight. (With a small model, a camera tripod might serve as a mount.) Tilt the model until the shadow of the peg points toward the intersection of the chosen time line and the chosen date curve. When the end of the peg's shadow touches this intersection, the model will show the same sun-shadow patterns as would occur on the time and date chosen.*

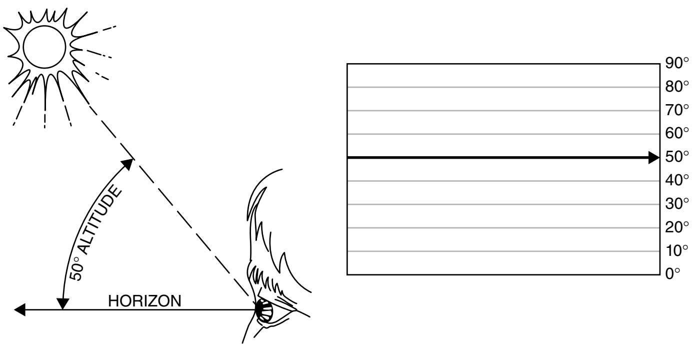


44°N LATITUDE

Fig. 6.11 *Equidistant (horizontal, polar) sunpath diagram for 44°N latitude. (Reprinted with permission from AIA.* Architectural Graphic Standards*, 11th ed. 2007. John Wiley & Sons.)*

2. The *equidistant projection* (*horizontal, polar*) is used almost exclusively in the United States because of the ready availability and wide acceptance of the sunpath charts provided in the Pilkington (formerly Libbey Owens Ford) Sun Angle Calculator. The observer moves around the skydome, like the sun's view to the earth. Figure 6.11 shows a sample equidistant projection sunpath diagram. A full set of equidistant projections is provided in Appendix D.3. This projection method is equally applicable to all latitudes, and a latitude-specific sunpath is needed for a location under study. The Pilkington Sun Angle Calculator sunpath diagrams are available in steps of 4° of latitude between 24° and 52° latitudes.
3. The *rectilinear projection* (vertical, cylindrical) is a two-dimensional graph of the sun's position in Cartesian coordinates. Azimuth is plotted along the horizontal axis and altitude on the vertical axis. The development of this type of chart is shown in Fig. 6.12. These charts are actually graphs superimposed on the eye of an observer. At the vertical center of each chart, the observer is looking due south. The horizon (a horizontal plane at the observer's eye level) is the line at the bottom of the chart. A set of rectilinear charts for several latitudes (from Mazria, 1979) is found in Appendix D.4.

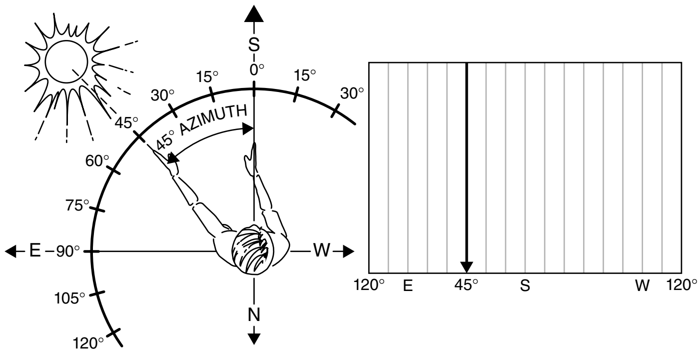
   These charts may also be used to easily determine the number of hours of greatest insolation, that is, what percentage of clear-day insolation is gained each hour by an unshaded *south-facing* vertical window (Fig. 6.13). This emphasis on south orientation calls attention to its useful characteristic of receiving *more* sun in winter and *less* sun in summer than any other orientation. To convert these percentages to actual heat gains, see Tables C.1 to C.10 (for *clear* days at a given latitude) or Tables C.19 and C.20 for *average* day data by climate station (January and July only).
4. The *stereographic projection* (circular, equal spacing) also represents the sun's changing position in the sky throughout the day and year. The format is like a fish-eye photograph of the sky pointed to the zenith directly above. The various paths of the sun throughout the year can be projected onto the sky, then "flattened." The principal advantage of this projection is that it is very simple to draw



(*a*) Altitude

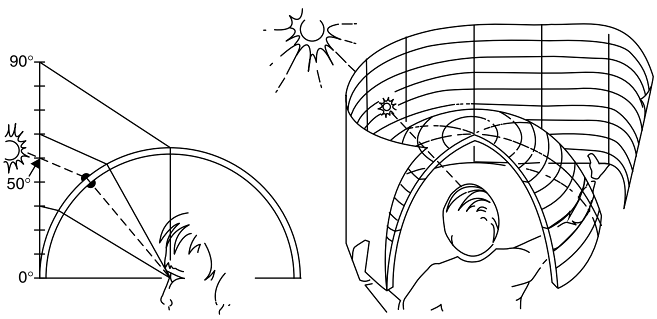
Two coordinates are used to locate the position of the sun in the sky. They are called the *altitude* and the *azimuth* (also called the bearing angle).

Solar altitude is the angle, above the horizon, of the position of the sun measured from the horizon. The horizontal lines on the chart represent altitude angles in 10° increments above the horizon.



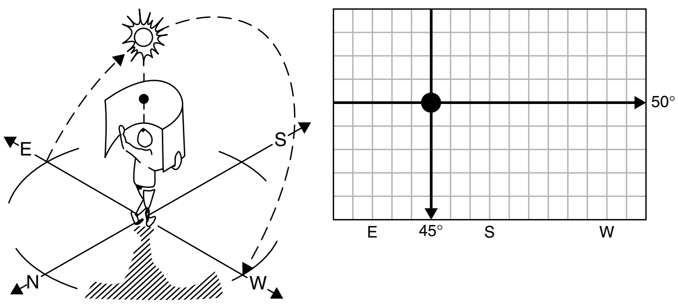
(*b*) Azimuth

Solar azimuth is the angle, along the horizon, of the position of the sun measured to the east or west from true south.



(*c*) Skydome

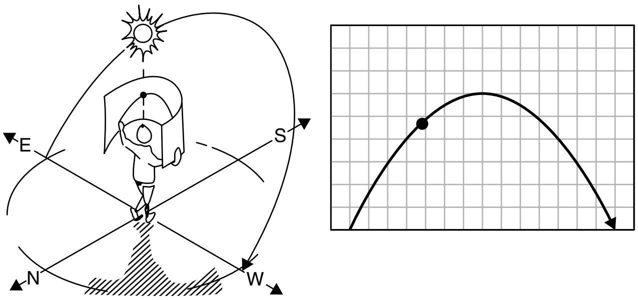
The grid on the chart thus represents vertical and horizontal angles of the whole skydome. It is as if there was a clear dome around the observer, and then the chart was peeled off this dome and laid flat.



(*d*) Sun Position

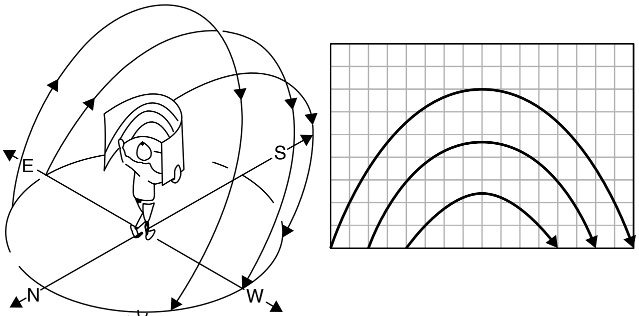
With the altitude and azimuth angles, the sun can be located at any point in the sky.

Fig. 6.12 *Illustrations (a) through (g) describe the development of the rectilinear sunpath chart (h) U.S. map showing cities along similar latitudes. (From Edward Mazria and David Winitsky. 1976.* Solar Guide and Calculator. *Center for Environmental Research, University of Oregon.)*



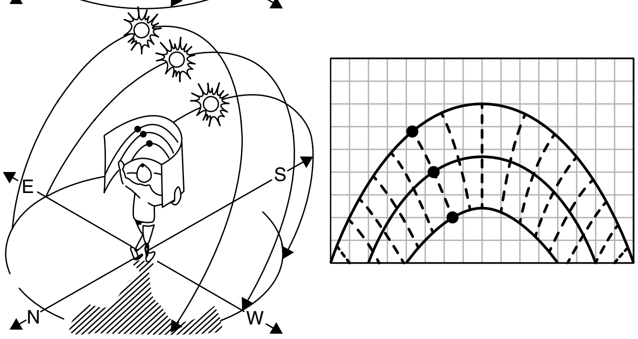
(*e*) Sun Path

By connecting the points of the location of the sun throughout various times of the day, the sun's path for that day can be drawn.



(*f*) Seasonal Paths

Thus, we can plot the sun's path for any day of the year. Those paths shown represent summer, fall/spring, and winter. The sun path is greatest during the summer when it reaches its highest altitude and rises and sets with the widest azimuth angle from true south. During winter, the sun is much lower in the sky and rises and sets with the narrowest azimuth angles from true south.

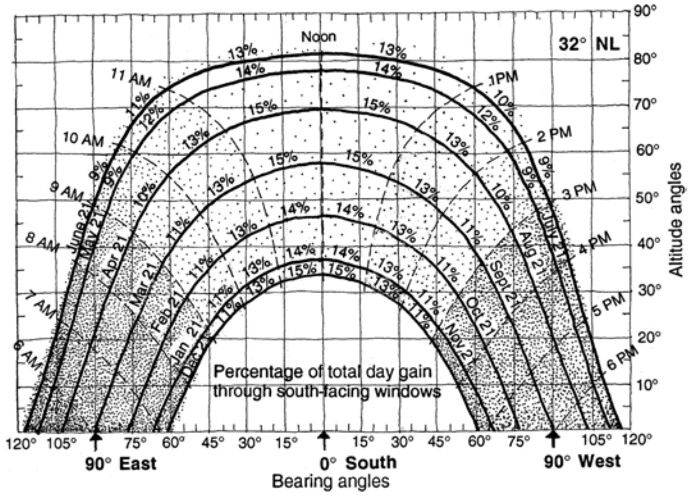


(*g*) Times of Day

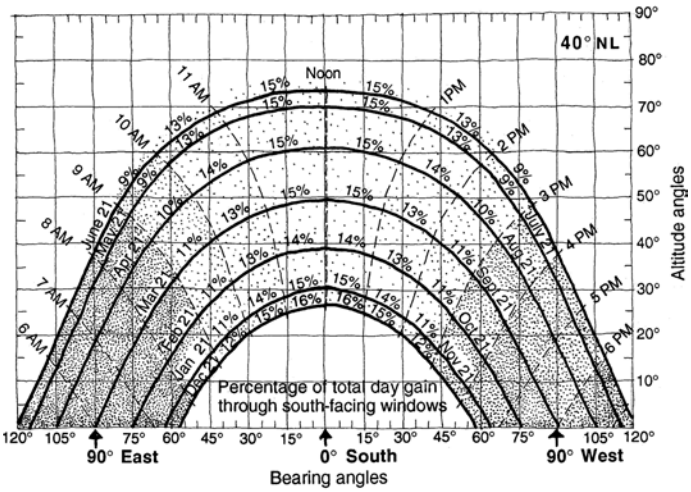
Finally, if we connect the hour lines on each path, we get the heavy dotted line which represents the hours of the day. This completes the sun chart. NOTE: The times on the sun chart are for solar time. This may vary from standard time as much as an hour and fifteen minutes for different locations and different times of the year. This is adequate for most practical uses of the sun chart. It is important to remember to at least use standard time when using the charts.

(*h*)

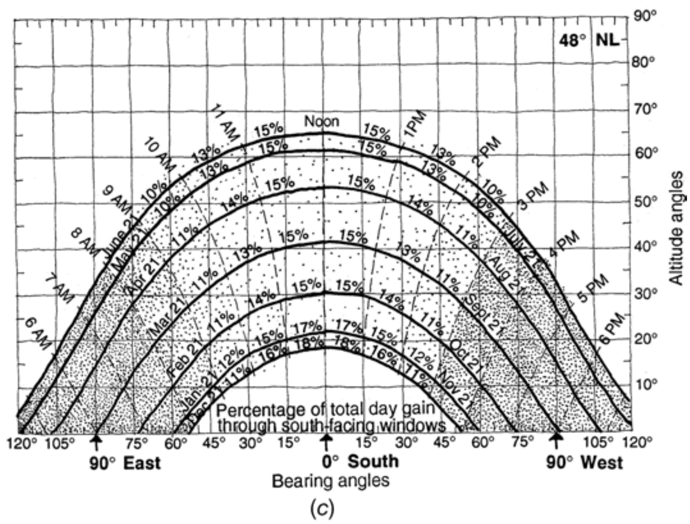
Fig. 6.12 *(continued)*



(a)



(b)



(c)

Fig. 6.13 *Sunpath charts for three latitudes (32°, 40°, 48°) show the approximate percentage of clear-day insolation for south-facing windows for each of the maximum hours of sun each month.*

sunpaths at any scale and for any latitude without having to rely on published sunpaths. Thus, for any serious sunshading design, a designer can prepare a large-scale sunpath chart at the exact latitude of a project and do accurate graphical analysis. For a detailed description of the method of preparing these charts, see Szokolay (1980).

The design of sunshading devices necessitates projecting the three-dimensional solar path onto a two-dimensional surface. Stereographic and equidistant projections are the most popular for sunshading analysis.

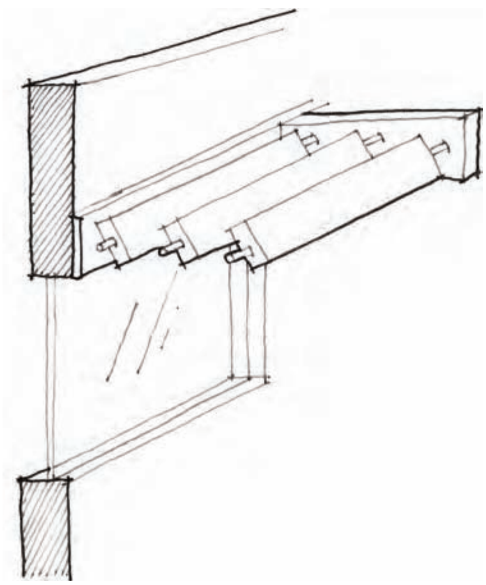
6.5 SHADING

Shading windows from solar heat gain is a key design strategy for passive cooling and to reduce cooling loads on active HVAC systems. Shading the opaque building envelope is also important, but since thermal resistance is usually greater through such elements than through glazing, the discussion in this section refers primarily to design strategies for shading windows oriented south, east, and west. Northern windows often also need shading devices, contrary to the myth that the north façade never receives direct beam radiation.

(a) Shading for Orientation

Because of the high altitude of the sun, the most effective shading device for south-facing windows during the summer is a horizontal overhang. On east- and west-facing windows, a horizontal overhang is somewhat effective when the sun is at high positions in the sky, but is not effective at low-altitude angles. A variety of shading devices are illustrated by the diagrams and examples in Figs. 6.14–6.18.

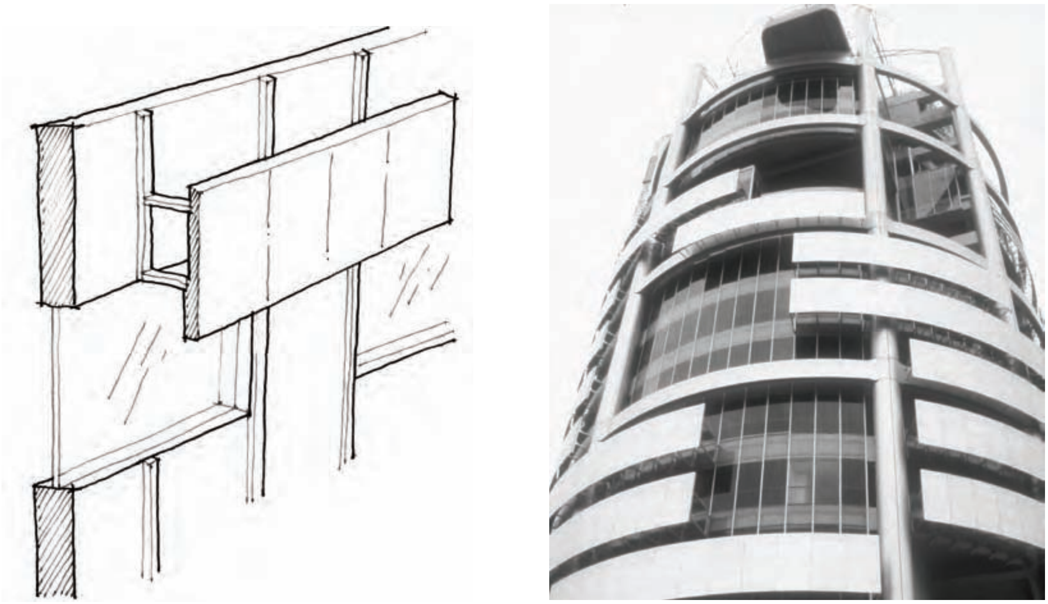
Direct solar gain through east- and west-facing windows can be an extraordinary heat gain liability and produce thermal and visual discomfort. During the early design stages, it is best to orient spaces to face north or south to avoid the east/west sun's low angle. If this is not possible, vertical fins are an effective strategy for east and west orientations. Eggcrate shading devices (a combination of overhangs and fins) provide optimal shading,



(a)

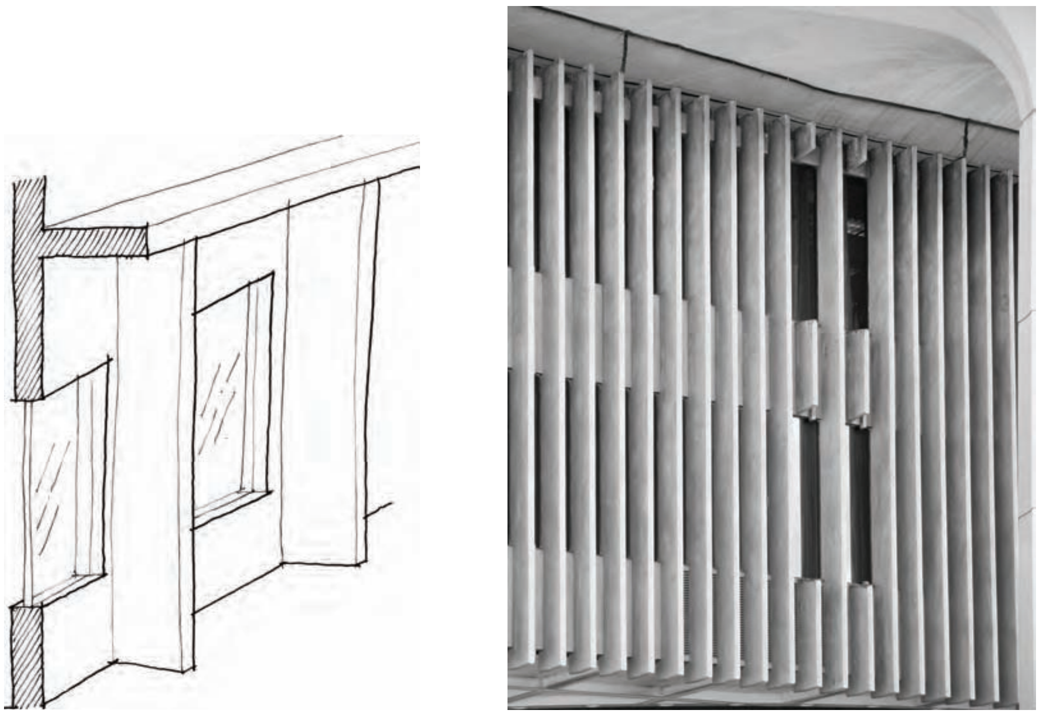
(b)

Fig. 6.14 (a) Overhang with horizontal louvers. (b) Horizontal louvers allow free air movement—office building in Honolulu, Hawaii. (Drawing by Erik Winter, photo by Alison Kwok; © Alison Kwok; all rights reserved.)



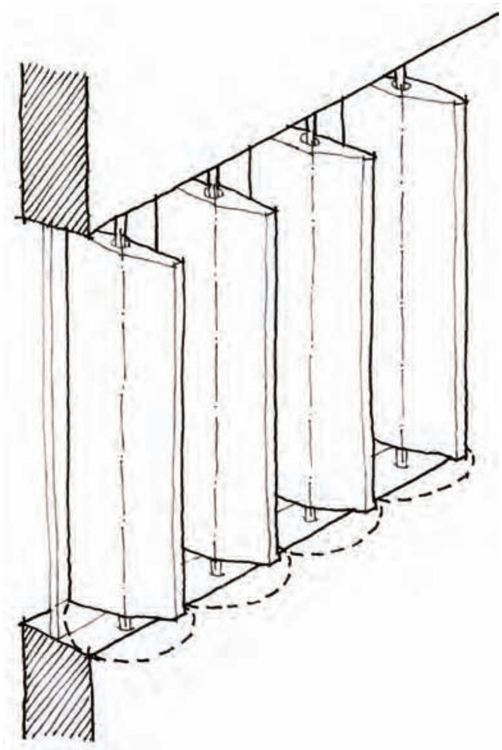
(a) (b)

Fig. 6.15 *(a) Overhang using a series of vertical panels. (b) Application of horizontal overhangs at the IBM Tower in Kuala Lumpur, Malaysia. (Drawing by Erik Winter, photo by Alison Kwok; © Alison Kwok; all rights reserved.)*



(a) (b)

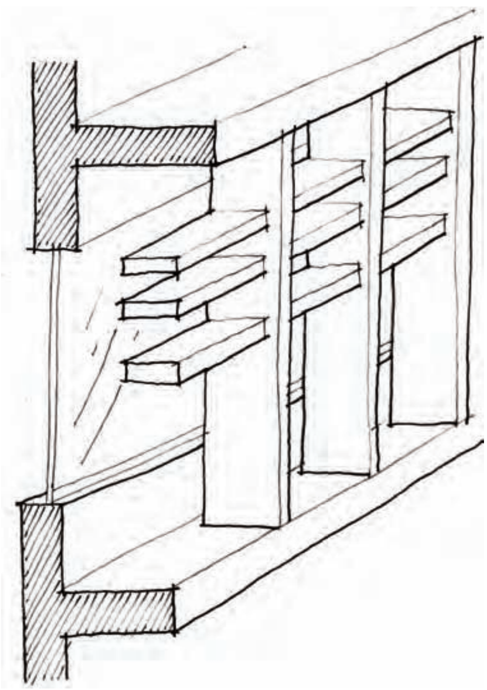
Fig. 6.16 *(a) Vertical fins. (b) Fixed vertical fins on a government building in Honolulu, Hawaii. (a) Drawing by Erik Winter (b) © Alisa Kwok; used with permission.*



(*a*)

(*b*)

Fig. 6.17 *(a) Movable fins. (b) Movable fins are positioned according to the sun's position at the Ala Moana office building in Honolulu, Hawaii. These effective shading devices were removed when the building was remodeled to make it look more contemporary. (Drawing by Erik Winter, photo by Alison Kwok; © Alison Kwok; all rights reserved.)*



(*a*)

(*b*)

Fig. 6.18 *(a) Eggcrate shading device. (b) Modified eggcrate to allow air movement and lighter structure at the Board of Water Supply in Honolulu, Hawaii.(a) Drawing by Erik Winter (b) © Alisa Kwok; used with permission.*

(a)

(b)

Fig. 6.19 *Integration of eggcrate shading devices into the envelope at (a) the Hawaii Medical Services Association building in Honolulu, Hawaii, and (b) the University of Arizona library in Tucson. (Photos by Alison Kwok; © Alison Kwok; all rights reserved.)*

particularly in hot climates (Fig. 6.19). North-facing windows receive direct solar radiation in the summer in the early morning and near sunset, when the altitude of the sun is very low. For shading on the north side at these times, vertical fins are most effective.

(b) Operable Shading Devices

Operable exterior shading devices are useful because they respond to daily and seasonal variations in solar and weather patterns in ways that fixed shading devices simply cannot do. The operation of a movable shading device can be as simple as twice-a-year adjustment—for example, manually extending roller shades, awnings, rotating fins, or louvers at the beginning of summer and retracting the shade after the hot season has ended (in fall). These devices are very effective at blocking low sun angles from the east or west. More complex movable devices are typically on automated daily and seasonal programs. Although many facility managers are of the opinion that movable exterior shading devices require high maintenance and are prone to malfunctioning, the designer can apply appropriate technology to provide a low-maintenance solution.

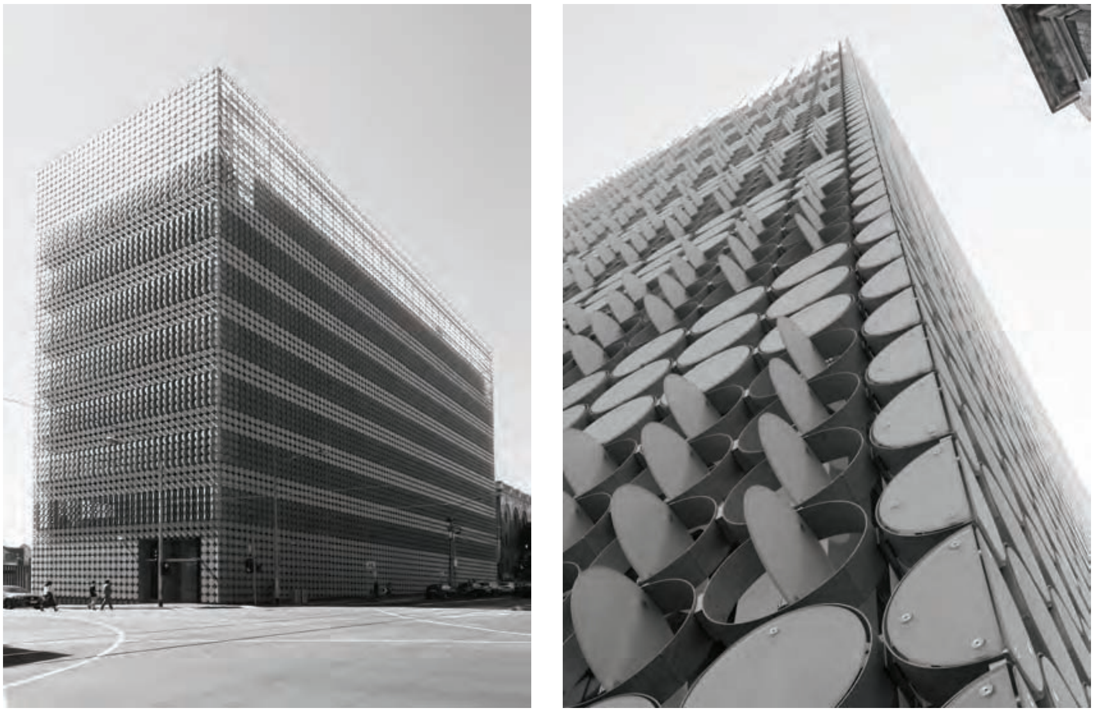
Designers can also situate deciduous trees and vines at key locations around a building, which will act as natural shading devices with a natural cycle for shade in the summer and loss of leaves in the winter (Fig. 6.20). Plants have the advantages of costing little, reducing glare, providing an attractive connection to nature, and reducing exterior surface (wall and ground) temperatures.

The City of Melbourne, Australia, has worked to become one of the world's greenest cities, initiating several programs to support commercial building owners' efforts to retrofit their properties with modern, energy-efficient technologies; to assist residents with recycling and water conservation; and to implement an urban tree plan, pilot programs for green roofs, water catchment, and green transport. Many buildings in the last 15 years have developed unique shading devices while also promoting eco-living (Fig 6.21–Fig. 6.26).

Fig. 6.20 *Vines grow on an exterior structure at the Finnish Embassy in Washington, DC. (© Erica Ling; used with permission.)*

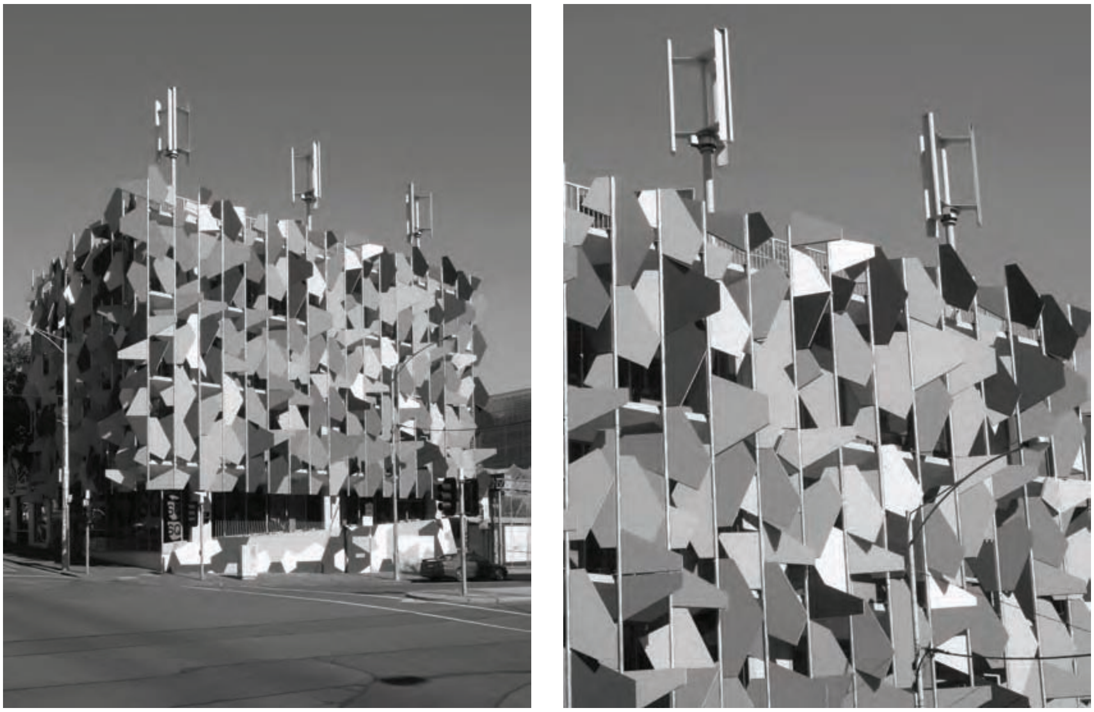
(*a*) (*b*)

Fig. 6.21 *(a) The Forte Apartments building features solar control, rainwater catchment, vegetable gardens, and bike sharing, and is the world's largest cross-laminated timber building. (b) Overhang and fin design create dramatic shadows on the façade. (Lend Lease, 2013.) (© Toshi Woudenberg; used with permission.)*



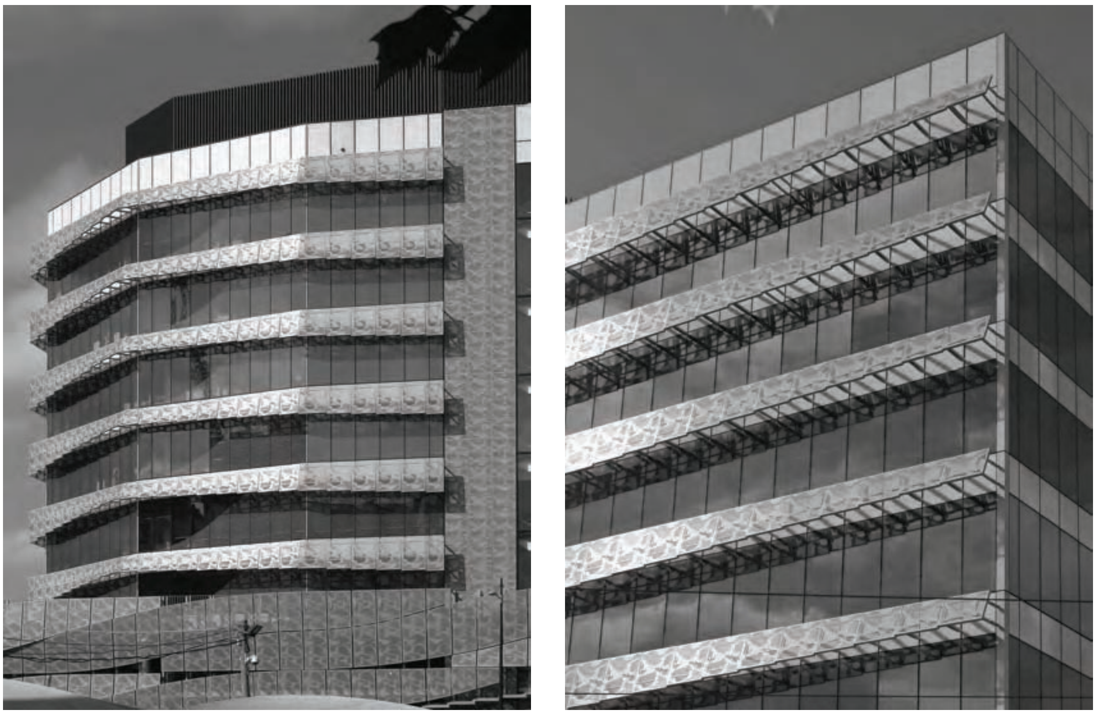
(*a*) (*b*)

Fig. 6.22 *(a) Sandblasted glass disks make up the exterior shading skin of the Design Hub at the Royal Melbourne Institute of Technology (RMIT). (b) The disks can rotate and meet climate and solar needs. (Sean Godsell Architects, 2012.) (© Toshi Woudenberg; used with permission.)*



(*a*) (*b*)

Fig. 6.23 *(a) Colorful, jagged shading panels cover the exterior of the Pixel Building. (b) The fragmented fins are one of many strategies for this high-performance building, which is designed to capture precious rainwater and filter it through native grasses covering 75% of the roof's surface. Note also the vertical axis wind machines. (Studio 505, 2010.) (©Toshi Woudenberg; used with permission.)*



(*a*) (*b*)

Fig. 6.24 *(a) Overhang shades undulate across the Melbourne Water Headquarters. (b) Sunshades are screens shading a substantial amount of glass. The building also features innovative water-conserving toilets. (Woods Bagot, 2012.) (© Toshi Woudenberg; used with permission.)*

(*a*) (*b*)

Fig. 6.25 *(a) A triangular pinwheel grid system on Federation Square employs a series of fractal shapes intended to be viewed as a dynamic façade. (b) Three cladding materials: zinc, glass, and sandstone tiles are used on the façade. (LAB Architecture Studio, 2002.) (© Toshi Woudenberg; used with permission.)*

(*a*) (*b*)

Fig. 6.26 *(a) A biomimicry concept was developed for Council House 2 (CH2) as a study of mediation between the environment and its occupants in a 10-story office building. (b) Operable, recycled timber shutters shade against the low, direct rays from the west. (Melbourne City Council and DesignInc, 2006.) (© Toshi Woudenberg; used with permission.)*

6.6 SHADOW ANGLES AND SHADING MASKS

Altitude and azimuth angles are very useful in understanding solar position and sunpath diagrams, but are much less useful in defining the shadow angles cast by a projection on a wall exposed to the sun. More angles come into play with shading device design.

(a) Shadow Angles

When designing shading devices, the geometry of the device itself and its relationship to the face of a building produce a number of angles relative to the desired shadow being cast. Since there is no universal nomenclature for these relationships, the angles involved in the design of shading devices will be very carefully defined. Refer to Fig. 6.27, which shows the shadow cast by a horizontal overhang on a wall exposed to sunlight. Note that the shadow is defined by two angles: the *vertical shadow angle* (VSA), which indicates the position of the leading edge of the shadow as defined from the leading edge of the overhang, and the *horizontal shadow angle* (HSA), which defines the leading edge of a shadow cast by a vertical element (indicated by a dashed line) as defined with respect to that element's leading edge. The terms *vertical shadow angle* and *horizontal shadow angle* are in use throughout the world, although in the United States the vertical shadow angle is also known widely as the *profile angle* because it is so designated on the Pilkington Sun Angle Calculator.

Figure 6.28 shows the same information in slightly different form; line *DA* is the shadow cast by line *DE*, which is the intersection between a horizontal projection and a vertical projection. This line is particularly important in determining the required extent of a shading element, as will be shown in the following sections.

(b) Shading Masks

A shading mask is a sunpath chart (horizontal projection) that shows the shadow cast by a particular shading device, as shown in Fig. 6.29. For a horizontal shading device, the leading edge of the shadow cast by all horizontal elements with the same VSA (profile angle) projects as a segmental line, and when plotted on the sunpath chart, it is shown as a segmental mask. To draw this segment, a protractor is required. The Pilkington Sun Angle Calculator includes a profile angle protractor (an overlay to the sunpath chart) to draw the required segment. With no shading, there is no shadow, the VSA is 90°, and no segment exists. With a very deep overhang, the VSA approaches 0° and the *unshaded* area shrinks.

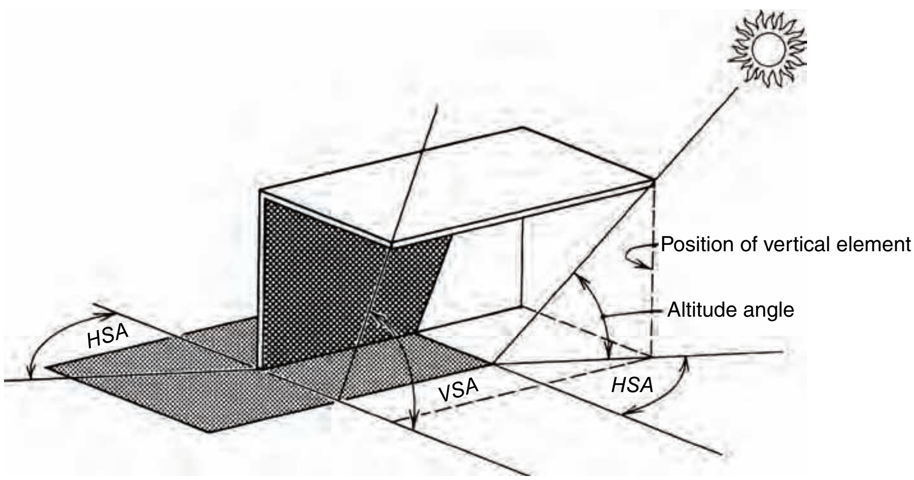


Fig. 6.27 *The shadow cast by a horizontal overhang is best defined by the vertical shadow angle (VSA) and the horizontal shadow angle (HSA). The VSA is also known as the profile angle in the United States.*

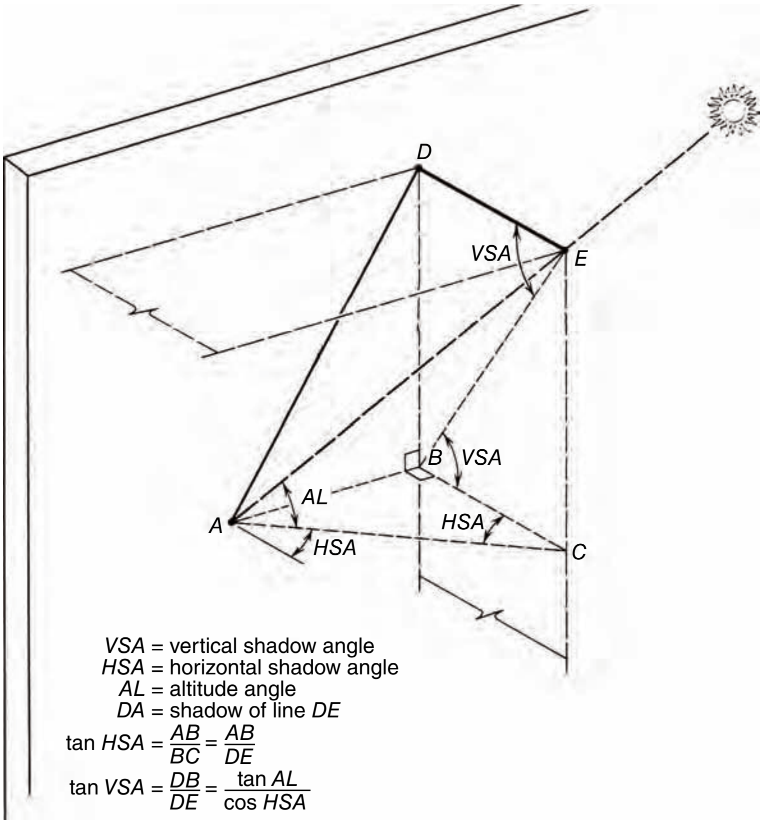


Fig. 6.28 *The shadow* DA *cast by the intersection line* DE *between a horizontal and a vertical shading element defines the edge of each of these shadows.* DE *can also be thought of as a pin, normal to and extending from the wall, casting a shadow,* DA, *on the wall. The location and size of line* DA *are best defined in terms of angles VSA and HSA.*

For vertical shading elements, such as fins (Fig. 6.29*b*), the leading edge of vertical shading elements forms a shadow, shown as radii projecting from the center, which forms an angle HSA, from a line normal to the wall. These radial lines can be drawn with the assistance of an ordinary protractor or by use of the protractor in Fig. 6.29*c*. The full segments and full radial lines of the shading masks are of *infinitely long elements*, which, of course, do not actually exist. Shading masks that appear in the literature (Olgyay and Olgyay, 1951; AIA, 2007) are frequently drawn as if for infinite elements, and the masks must be truncated for real-world shading design.

(c) Use of Shading Masks

A shading mask is drawn on some transparent medium (e.g., paper or plastic sheet) and laid on top of a sunpath diagram for the proper latitude *drawn to the same scale* (see Fig. 6.30, which illustrates the placement of a shading mask). Its center point is placed on the center point of the sunpath diagram, and it is rotated until its facing direction (the direction normal to the wall) is aligned with the appropriate azimuth line on the sunpath diagram. Assuming that the shading mask has been correctly drawn to provide shading for the window (typically 50% or 100% coverage), the shaded hours for the window and device in question can then be read directly from the underlying sunpath diagram, as summarized in Table 6.1. (This is why the shading mask must be drawn on a transparent medium.)

It is extremely important to note that a horizontal overhang shading element the same width as a window can provide full shade for the window only

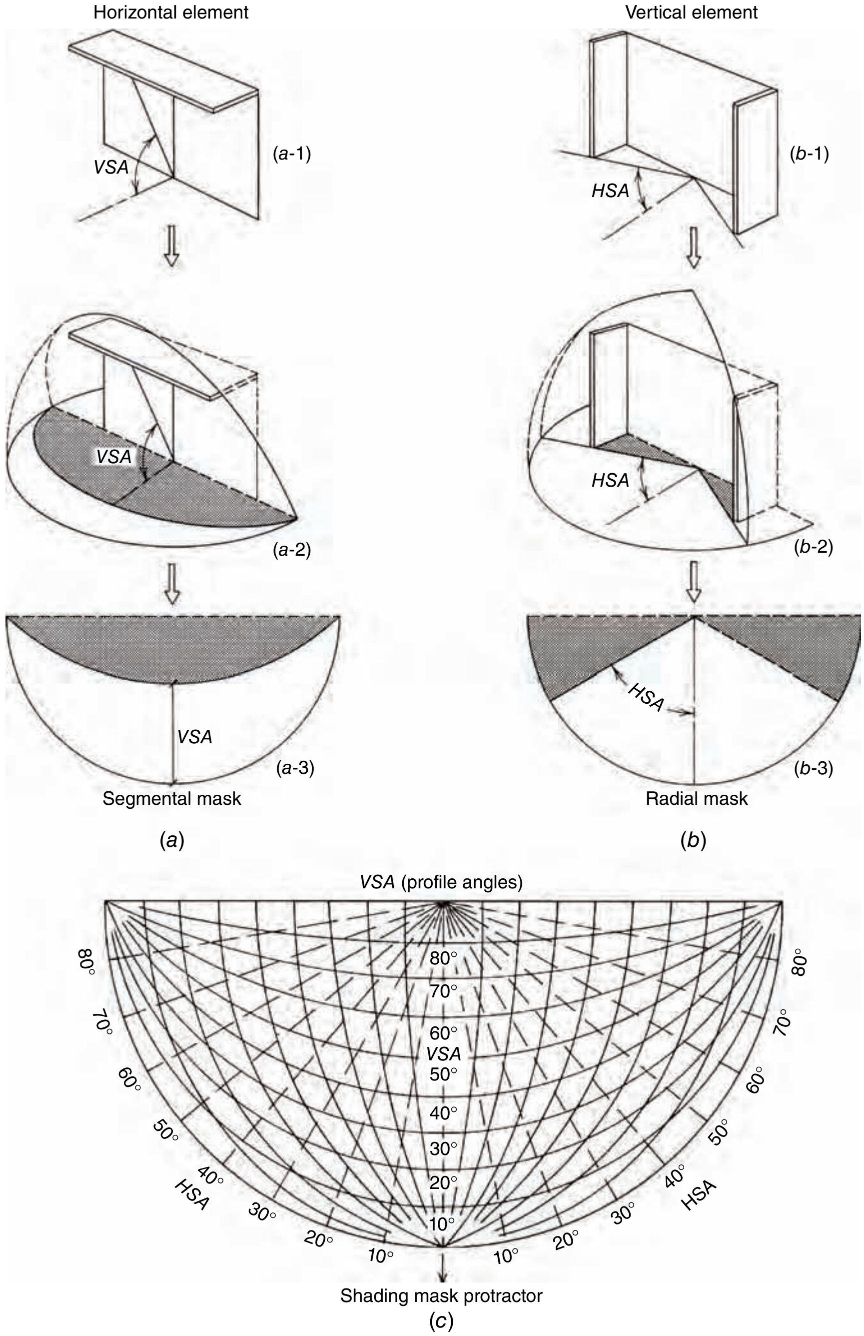


Fig. 6.29 *A shading mask is the horizontal projection of the shadow cast by the elements with the same VSA or HSA. Thus, any infinitely long horizontal element with the VSA shown in (*a*-1) will have a shading mask, as shown in (*a*-3). Similarly, any infinitely high vertical elements with the HSA shown in (*b*-1) will have the shading mask shown in (*b*-3). A protractor (*c*) is required to draw the segmental horizontal element mask properly.*

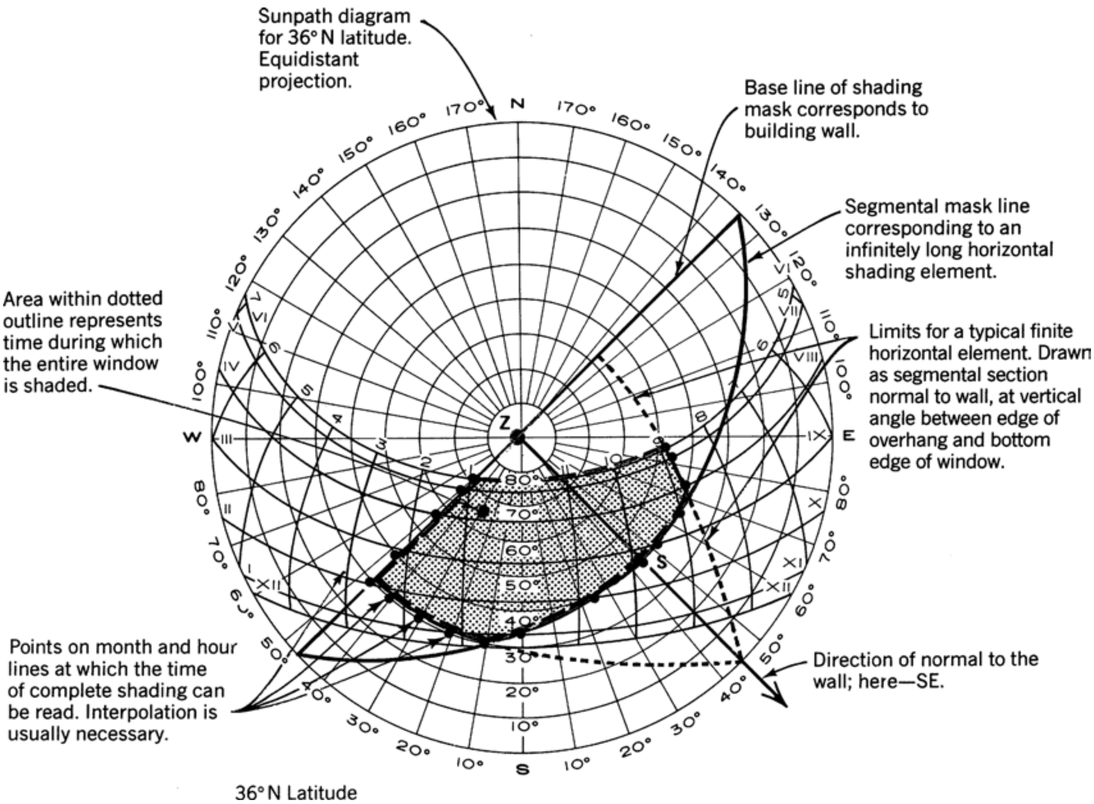


Fig. 6.30 *A shading mask for a typical horizontal overhang on a window is laid over a sunpath diagram to permit determination of the shaded hours. The mask is drawn to provide 100% shading for the entire window. The hours during which the entire window is shaded are determined by the intersection of the mask perimeter with the date/hour lines of the sunpath diagram, and are tabulated in Table 6.1. Only during the hours falling within the dotted area is a window fully shaded by an overhang element that is as wide as the window. The shading element shown here is not symmetrical about the center, indicating that an extension to the left was used to provide a larger shade period after noon. This is typical for east-facing windows and is reversed for western exposures.*

when the sun is exactly opposite the window (when the solar-window azimuth is 0°). This situation occurs for only an instant (Fig. 6.31). At all other times, some part of the window will be exposed to the sun. To provide full shading for more than an instant with a horizontal element and no vertical (side) elements, *an overhang must extend beyond the sides of the window*. The amount of such an extension can be determined both graphically and analytically. Since graphic solutions are amply treated in the literature (Harkness and Mehta, 1978; Lim et al., 1979; Cowan, 1980), the focus here is the analytic solution. In reviewing this discussion, keep in mind the requirement that shading masks for 100% coverage must be prepared so that the extremities of the opening are shaded.

TABLE 6.1 Time of Day When Window Is Fully Shaded

With Required Overhang Extensions			With Element Same Width As Window
Date	**From**	**To**	**Time**
21 June	0900	1240	1115
21 July/May	0850	1250	1100
21 Aug./Apr.	0845	1330	1035
21 Sept./Mar.	0940	1400	0955
21 Oct./Feb.	1040	1410	—
21 Nov./Jan.	12N	1300	—
21 Dec.	1230		—

(d) Designing Finite Horizontal Shading Devices

Although any percentage of window shading coverage is possible, most shading devices are designed to give either 50% or 100% coverage. Deciding upon shading coverage is the first step in design.

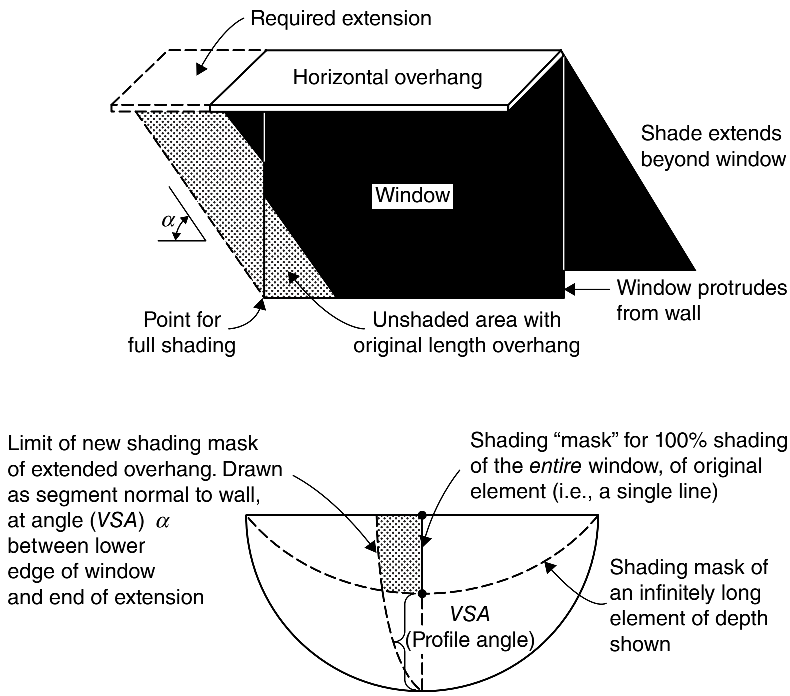


Fig. 6.31 *A horizontal overhang with sufficient depth to provide 100% shading can provide full shading only when the sun is exactly opposite a window. At any other time, part of the window will be exposed to the sun. Full shading from low early morning or late afternoon sun is not possible with horizontal elements.*

The second step is to establish the required *depth* of the shading device (the distance it projects from the wall). Figure 6.32 shows how the required depth and the corresponding segmental mask are determined. At times, because of window areas left unshaded by the original overhang, it is necessary to determine the required side extensions beyond the window's edges.

Due to the symmetry of solar motion about the ecliptic, the position of the sun is symmetrical on both sides of its maximum/minimum positions, that is, the solstices. Thus, the sun's position on

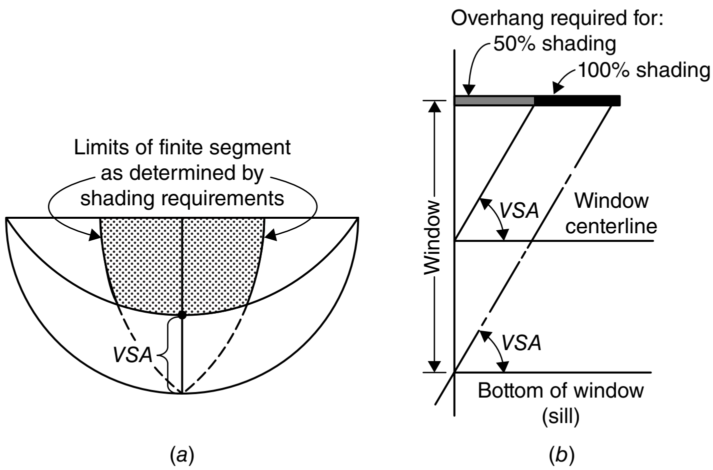
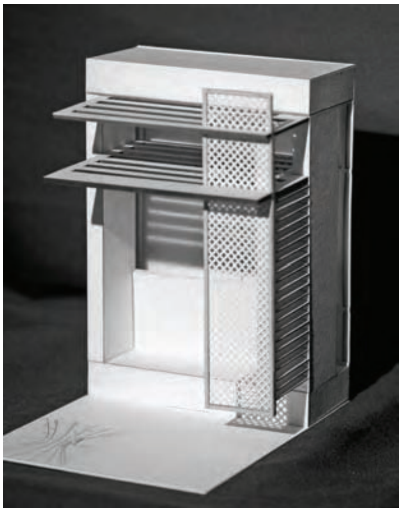
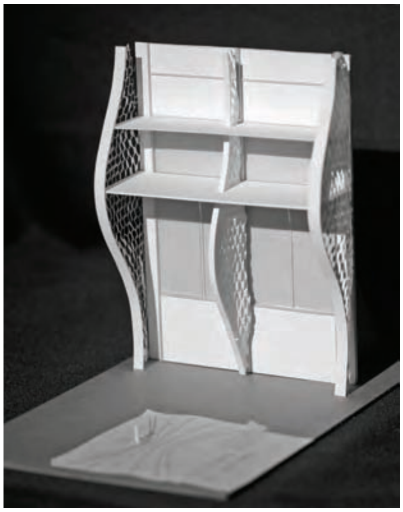


Fig. 6.32 *One way to find the required depth of a horizontal overhang is to establish the required segmental shading mask (a) and read the VSA (profile angle) off the protractor that corresponds to the segment. Draw a wall section (b) to scale with the VSA. The VSA can be drawn for 50% shading coverage, 100% coverage, or any other value. The depth of the overhang can be measured directly from the section. Alternatively, if the overhang depth is known, the segment can be drawn.*



(*a*)

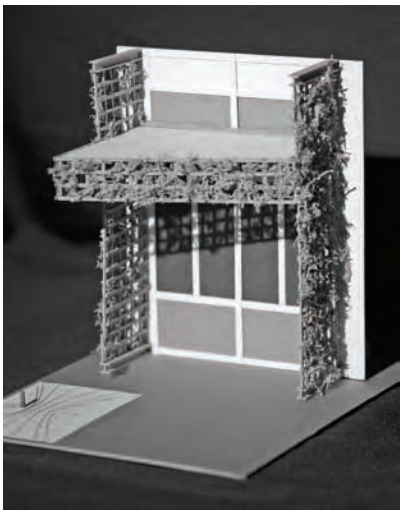


(*b*)

(*c*)

(*d*)

(*e*)



(*f*)

Fig. 6.33 *Examples of shading device models (a–f) illustrate a variety of design responses to orientation, shading requirements, and view for a university building located at 44°N latitude. (Photos by David Bisers; © Alison Kwok, all rights reserved.)*

May 21 is the same as on July 21, since both dates are 1 month from the summer solstice. As a result, any *fixed* shading device will give the same shade in the spring (before June 21) as in the summer (after June 21). Since in many locations spring is cool, desired late summer shading will produce spring shading that *may not* be desirable. Solutions to this apparent dilemma are either to use a movable or a variable-size fixed shading device or to compromise on the amount of shading—that is, to design for 50% shading for late summer (and early spring) and 100% shading for early summer (and late spring).

(e) Design Approaches

In addition to the approach just described, design might start with conceptual sketches of an appropriate shading device. As the sketches are developed into scaled drawings, a sectional drawing will show the geometry of the building. The VSA for 100% shading would be an angle from the windowsill to the outer edge of the overhang. Once the VSA is established, a shading mask can be created and overlaid onto the appropriate sunpath chart to determine whether there is adequate shading during specific times of the day and year. A more detailed description of this design process is found in Olgyay and Olgyay (1951).

Shading devices can greatly enrich the aesthetics of a building as well as improve performance. Examples of shading device models for various orientations (Fig. 6.33) show a range of shading design solutions for a building in a temperate climate.

References and Resources

AIA. 2007. Ramsey, C. G.and H. R. Sleeper. *Architectural Graphic Standards*, 8th ed. American Institute of Architects/John Wiley & Sons. Hoboken, NJ.

Cowan, H. J. (ed.). 1980. *Solar Energy Applications in the Design of Buildings*. Applied Science Publishers. London.

Geomagnetic Maps (showing magnetic deviation). http://www.geo-orbit.org/sizepgs/magmapsp.html

Harkness, E. and M. Mehta. 1978. *Solar Radiation Control in Buildings.* Applied Science Publishers. London.

Lim, B. P., K. R. Rao, K. Tharmaratnam, and A. M. Mattar. 1979. *Environmental Factors in the Design of Building Fenestration*. Applied Science Publishers. London.

Mazria, E. 1979. *The Passive Solar Energy Book: A Complete Guide to Passive Solar Home, Greenhouse and Building Design*. Rodale Press. Emmaus, PA.

Olgyay, A. and V. Olgyay. 1951. *Solar Control and Shading Devices*. Princeton University Press. Princeton, NJ.

Online Sun Angle Calculator. http://www.susdesign.com/sunangle/

Pilkington Sun Angle Calculator. 1975. The Pilkington Sun Angle Calculator (formerly the Libbey Owens Ford Sun Angle Calculator) is available through the Society of Building Science Educators (SBSE). http://www.sbse.org/resources/sac/

North American Sundial Society (information on clock vs. solar time). http://sundials.org/

Szokolay, S. V. 1980. *Environmental Science Handbook*. Halsted/John Wiley & Sons. New York.

University of Oregon (sunpath diagram software). http://solardat.uoregon.edu/SunChartProgram.html

U.S. Naval Observatory (complete sun and moon data for one day). http://aa.usno.navy.mil/data/docs/RS_OneDay.html

CHAPTER 7

Heat Flow

UNDERSTANDING HEAT FLOW IS FUNDAMENTAL TO ALL aspects of climate control. Chapter 4 addresses heat flows to and from the body that affect thermal comfort. Chapters 9, 10, and 11 deal in part with heat flows to, from, and within various elements of passive climate control systems. This chapter deals with heat flows through building envelopes, both through the materials of the building skin and by way of infiltration of outdoor air that replaces conditioned indoor air. Basic concepts and calculations of heat flow are presented in this chapter, whereas applications of these concepts (passive solar heating, passive cooling, active HVAC system/equipment sizing, seasonal energy usage) are found in subsequent chapters. Numerous data tables that accompany this chapter are presented in Appendix E.

7.1 THE BUILDING ENVELOPE

From a building science perspective, the exterior enclosure (or envelope) of a building consists of numerous materials and components that are assembled on site to meet the intents of the owner and the design team. A building envelope typically includes some prefabricated components (such as windows and doors) that are available off the shelf and have well-defined and tested thermal performance characteristics. The typical envelope also includes materials in a variety of forms (sheets, blocks, bulk products, membranes, etc.) that have been site-assembled to meet design requirements. These components and materials may be assembled into commonly used configurations with generally understood performance, or into configurations unique to a given project and of uncertain performance. The job of envelope thermal analysis is to ensure that a proposed envelope will meet the project's design intent and criteria (including building codes).

From a functional perspective, the envelope of a building is not merely a two-dimensional exterior surface; it is a three-dimensional transition space—a theater where the interactions between outdoor forces and indoor conditions occur under the command of materials and geometries. Sun and daylight are admitted or rejected; breezes and sounds are channeled or deflected; and rain is repelled or collected. This transition space is where people indoors might experience something of what the outdoors is like at the moment, as well as where people outside can get a glimpse of the functions within. Figure 7.1 shows an example of an envelope that is a transitional space, not merely a surface. The more suited the outdoors is to comfort, the more easily indoor activity can move into this transition space. At building entries, a person will be especially aware of the difference between indoors and outdoors during the passage between the two conditions.

Fig. 7.1 *The envelope is more than a surface. This south-facing office façade in Oregon forms a microclimate zone that buffers the transition between indoor and outdoor conditions. Groundcover plants at eye level for seated occupants and deciduous vines overhead give a seasonally changing view to the outdoors through a façade that also admits winter sun, year-round daylight, and summer breeze. (Photo by Amanda Clegg.)*

7.2 BUILDING ENVELOPE DESIGN INTENTIONS

Called by their familiar names, the basic components of a building envelope include windows, doors, floors, walls, and roofs. On closer inspection, windows can include skylights, clerestories, screens, shutters, drapes, blinds, diffusing glass, and reflecting glass—an array of components that determines how the envelope does its job of making the transition between inside and outside. Norberg-Schulz (1965) suggests that a component can more fundamentally be thought of in terms of its design intent relative to the exchange of energies: As a *connector*, *filter*, *switch*, *or barrier*.

> In general, we define a *connector* as a means to establish a direct connection, a *filter* as a means to make the connection indirect (controlled), a *switch* as a regulating connector, and a *barrier* as a separating element. . . . An opaque wall thus serves as a filter to heat and cold, and as a barrier to light. Doors and windows have the character of switches, because they can stop or connect at will. (p. 113)

In addition to these historic envelope intents, a new option is emerging—the *transformer.* A transformer is intended to convert an environmental force (such as solar radiation) directly into a different and desirable energy form (such as electricity). A photovoltaic roof shingle is an example of a transformer (it does more than simply connect, filter, block, or switch).

The fundamental range of choices surrounding envelope intent and components can be illustrated by two opposite design concepts: the *open frame* and the *closed shell*. In harsh climates (or where unwanted external influences such as noise or visual clutter abound), the designer frequently conceives of the building envelope as a closed shell and proceeds to selectively punch holes in it to make limited contact with the outdoors. Such an approach might be called *barrier-dominated*. When external conditions are very close to the desired internal ones, the envelope often begins as an open structural frame, with pieces of building skin selectively added to modify only a few outdoor forces. Such an approach might be called *connector-dominated*. (Note that a connector, filter, or barrier for one natural force may change its role for another force: Glazing may be a connector to daylight but a barrier to wind.) The open-frame or the closed-shell approach to envelope design, when combined with material availability and the influence of local culture, can produce a distinct regional architecture, as shown in Fig. 7.2.

With a wide range of energy sources, building materials, and mechanical equipment available, it is possible to build connector-dominated buildings anywhere, regardless of the climate. The consequences of the resulting energy consumption can be severe. In contrast, if defending against outdoor conditions becomes an overriding consideration, barrier-dominated envelopes may be appropriate in any climate. The designer's use of connectors, filters, and barriers is basic to the design of building exteriors. With the addition of switches that allow the envelope to respond to changing conditions and transformers that respond to building needs and site resources, a liveliness can result that makes a building an attractive addition to its environs.

Switches are a designer's way of allowing an envelope to respond in a variable manner and/or giving building occupants some control of their own environment. Seasons and functions change; people are unpredictable. If the designer has carefully considered the range of choices that a switch will provide, successful user control of that switch is possible. Building skins plentifully supplied with switches become demonstrations that architecture is a performing art, not simply static sculpture. Figure 7.3 shows a remarkably integrated switch-dominated envelope in vernacular architecture.

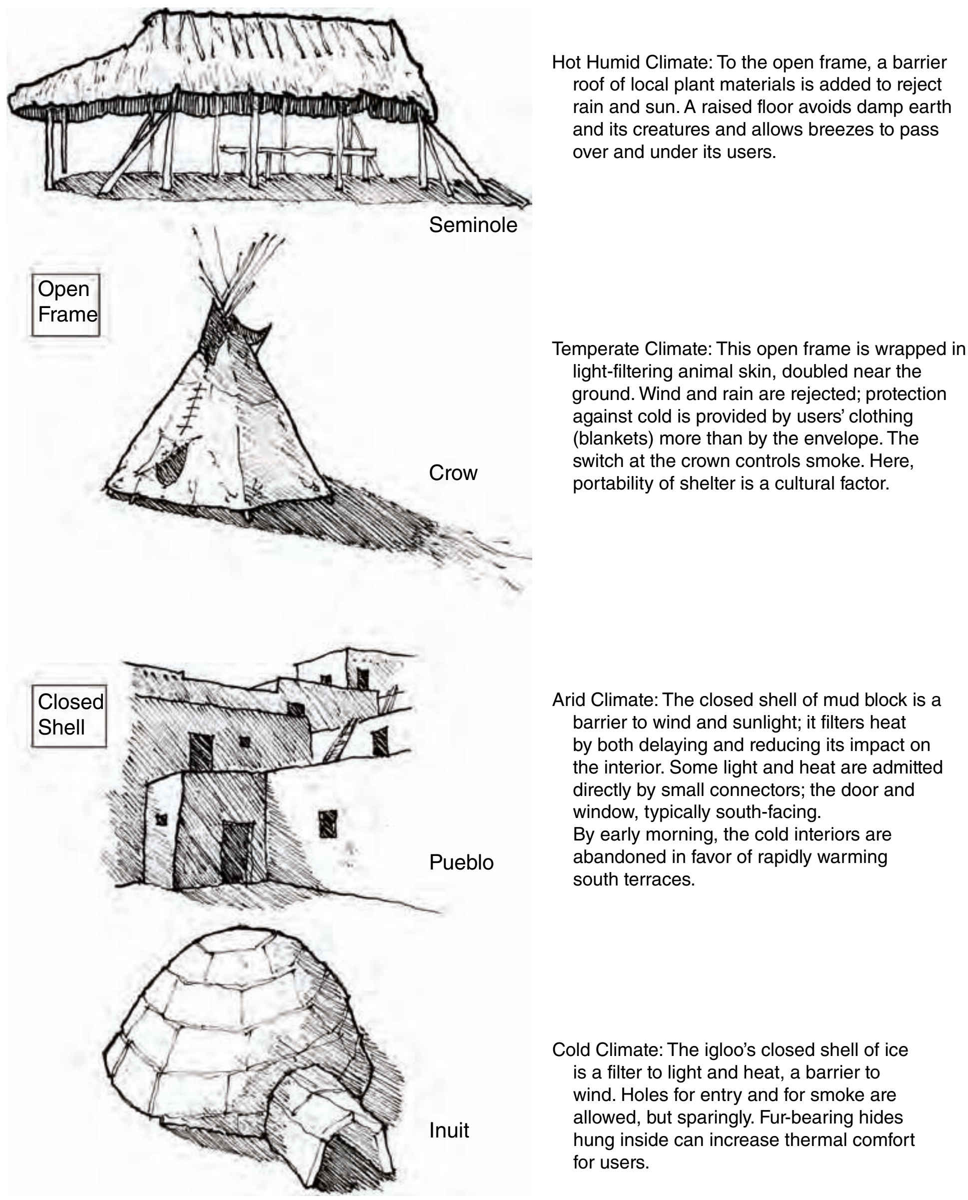


Fig. 7.2 *Open-frame (Seminole and Crow) and closed-shell (Pueblo and Inuit) envelope approaches are influenced by climate, materials, and culture. The influence of climate is dramatic, but material availability and cultural expectations also influence the envelope design solutions in these examples. (Drawing by Dain Carlson.)*

Solar control devices are perhaps the most common and visible switches. Awnings block direct solar radiation at some times and admit it at others. Opaque drapes can expose all of a window to incoming daylight on dark days or block out daylight entirely when desired. Translucent curtains can change bright sun into a diffuse light, or be drawn back to allow strong direct sun and shadow to be cast inside a room. Passive solar heating systems rely on switches to control incoming solar radiation on warmer days. Operable windows are a commonly used thermal switch. Ventilating switches may be separate from windows.

Visually, switches are a particularly promising source of three- and four-dimensional interest on a building's exterior. For the office buildings in Fig. 7.4, on which façade would the daily and seasonal changes be most visually evident? If it is easier

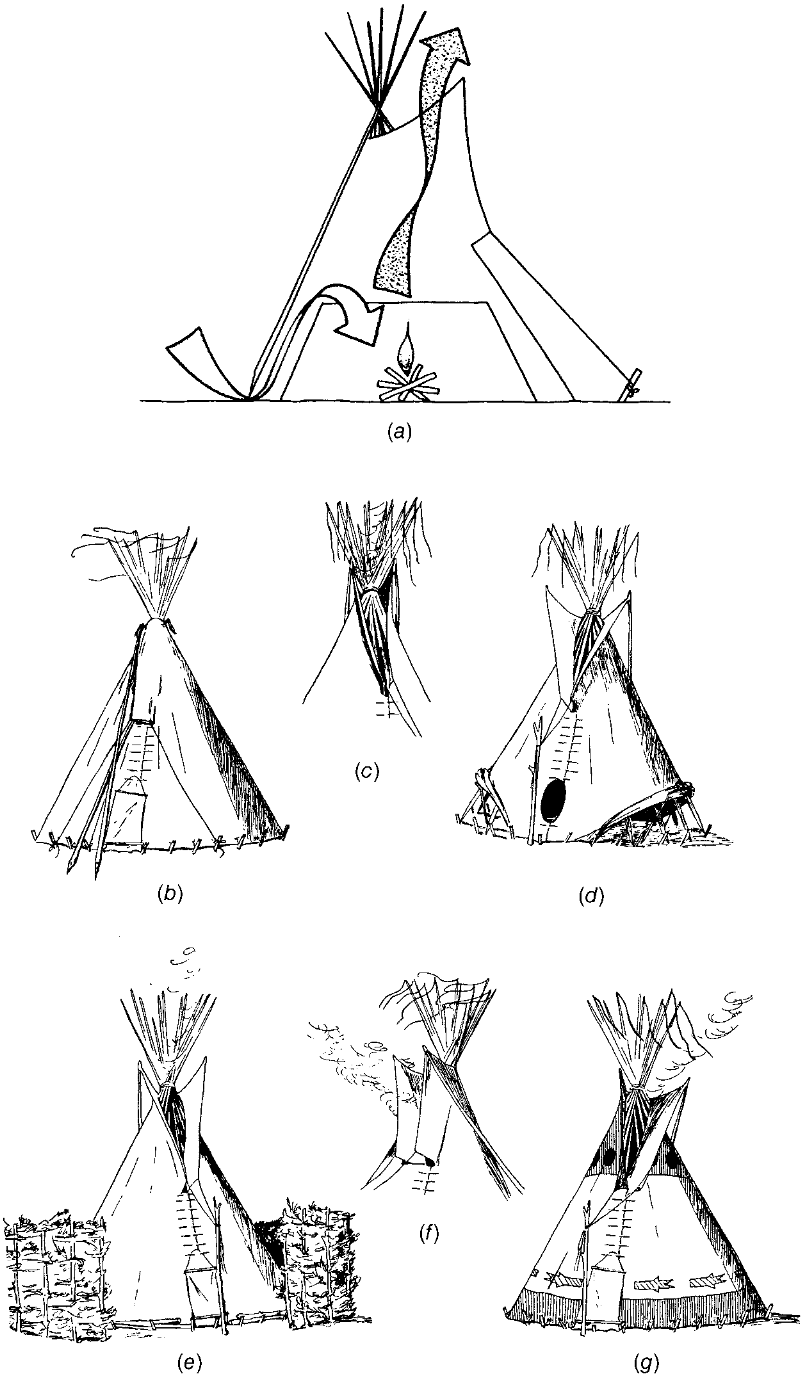


Fig. 7.3 *Thermal switches on the Great Plains. (a) With an interior fire, smoke flaps at the top are adjusted to vent the smoke, and an interior liner forces the cold combustion air entering at ground level to first rise along the sides of the tipi, gaining some warmth, before it moves across the occupants on its way to the fire. Six adjustments to the lightweight, translucent, and portable tipi are shown: The tipis in these diagrams are facing east, with their backs to the prevailing westerly winds. (b) In severe rainstorms, the smoke flaps at the top can be closed. (c) For ordinary conditions of west wind, the smoke flaps block the wind, thus creating suction to draw out the smoke. (d) In hot weather, breezes are admitted under the cover at the ground. (e) In extremely cold weather, a temporary windbreak can be added. (f) For the unusual wind or (g) southwest wind, the smoke flaps are manipulated to block wind, again encouraging smoke draw-out, as in (c). (Parts b–g from* The Indian Tipi: Its History, Construction, *and* Use *by Reginald and Gladys Laubin. Copyright 1957 by the University of Oklahoma Press.)*

(a)

(b)

(c)

(d)

Fig. 7.4 *Sun control for office buildings. (a) Shading switches both inside the glass (blinds) and outside the glass (awnings) are evident, and the windows themselves are operable. Awning use varies with window location and occupant needs and desires (New England Merchants' Bank; Shepley Rutan & Coolidge, Architects; demolished 1966). (b) Mechanized external shades provide filters and switches (Bateson Building, Sacramento, CA; Sym Van der Ryn). (c) Three-dimensional filters (overhangs) dominate the south façade (right) of this building at Boston University; the adjacent west windows (where overhangs are less effective) have only internal switches (blinds) deployed in a variety of positions. (Law and Education Building; Sert, Jackson and Gourley, Architects). (d) A two-dimensional filter of reflective glass equally sheathes all faces of this office tower, sending reflected solar radiation to the neighborhood below. Variability is removed from the envelope, and users are not involved in defining the outside–inside relationship (John Hancock Headquarters; I.M. Pei and Partners, Architects). (b) © Alison Kwok; all rights reserved; (a, c, d) photo by Stephen Tang.*

to imagine human beings working behind the windows of one building than of the other, might that suggest a more satisfactory work environment? Might more personal control of a window promote greater comfort and increased productivity?

Switches encourage interaction between people and their environments. This is usually satisfying to the users, who are able to select a desired exposure to the climate at a given moment. Yet without automation, supervision, or training in their use, switches can also be detrimental to system performance. Examples include a thermal shade in a passive solar heating system left closed on a sunny winter morning; a vent left open during the hottest hours in a high-mass, night-ventilated building; or an awning rolled up to expose a window to summer sun. People in buildings often use switches as they feel appropriate, as demonstrated in Fig. 7.5. Conventionally air-conditioned buildings typically do away with user-operated ventilating switches (operable windows) so that the system will instead function with a closely and automatically controlled flow of filtered outdoor air. Thermally efficient as this practice may be, it can also be a source of widespread dissatisfaction with air-conditioned spaces. Sealed windows greatly curtail people's contact with sounds, smells, and breezes from the outdoors. This is frequently beneficial in urban areas, yet on beautiful days it can be very frustrating. A lack of switches can contribute to a feeling of helplessness regarding one's personal environment.

Passive heating and cooling systems are especially reliant upon switches, hence on the knowledge and cooperation of their users. These users often must base their manipulations of thermal switches at one point in time on the effect that will be needed at a later time. This practice, called *thermal sailing*, is similar to the actions of outdoor workers in the far north, who learn to unbutton their coats in the cold early hours of the workday *before* they begin to sweat. Sweat would soak their

Fig. 7.5 *Multiple window switches: shutters, curtains, inner shutters, operable windows, and planter boxes on the balconies overlooking Piazza dei Signori in Vicenza, Italy. (© Alison Kwok; all rights reserved.)*

clothing, with harmful results later in the day as temperatures fall rapidly near dusk.

Misjudgments in the design of passively solar-heated residences can result in extraordinarily high temperatures on a sunny day or uncomfortably cold nights without stored solar heat. For a building closely connected to its climate, the design of switches is also the design of an educational process for the users. The challenge is to involve, but not bind, the users in the management of their environment. Automated controls are a partial answer to this challenge; switches that are easy, fun, and obvious to use are another.

7.3 SENSIBLE HEAT FLOW THROUGH OPAQUE WALLS AND ROOFS

The flow of heat through a building envelope is highly variable. Heat flow varies broadly by season (heat generally flows *from* a building in winter and *to* a building in summer) and also hourly (as temperature, relative humidity, and solar radiation impacts change). The precise path of heat flow can also vary (through the numerous materials and assemblies of the building enclosure or by way of outdoor air entering the interior through intentional and unintentional pathways). These complexities must be considered by a designer who intends to deliver thermal comfort in an energy-efficient and environmentally responsible manner. The following discussion of heat flow will focus first upon the building skin (opaque elements, then transparent elements), followed by heat flow via air exchange.

In the 1970s, in the wake of global concerns about energy costs and availability, designers began placing increasing emphasis on the thermal performance of building enclosures. Buildings (and building performance) changed as a result of this focus. Tighter building envelopes resulted in decreased air leakage, leading to ongoing concerns about indoor air quality and "sick building syndrome." Today's building code requirements likely strike a fair balance between envelope energy efficiency and air quality requirements—although in the United States these two issues are addressed by separate codes/standards. A typical new North American building loses somewhat more winter heat via incoming fresh air than it loses through its skin. In summer it gains somewhat more heat through its skin than it does via incoming fresh air (although this is very climate-dependent). This pattern is due in part to the importance of solar radiation to envelope heat gains in summer, and in part to the design outdoor–indoor temperature difference being much greater in winter than in summer (in most North American locations). The handling of latent (humidity-based) loads also influences these load patterns.

Sensible heat is a form of energy that flows whenever there is a temperature difference; it manifests itself as an internal energy of atomic vibration within all materials. Temperature is an indication of the extent of such vibration, essentially the "density" of heat within a material. Other forms of energy (such as solar radiation or sound) can be converted to heat and vice versa (within limits). Latent heat is heat that is used to change the state of (evaporate or condense) water. *Power* refers to the instantaneous flow of energy (at a given time). *Energy* refers to power integrated over time. Table 7.1 lists commonly encountered terms related to energy, power, and heat flow. Some of the units used to quantify heat, power, and energy are quirky. Nevertheless, time spent understanding these units will be useful to building design efforts.

(a) Static versus Dynamic; Sensible versus Latent

Although the general principles remain the same, analysis of heat flow under dynamic (rapidly changing) conditions is more complex than under static or steady-state (generally stable over time) conditions. The effects of heat storage within materials become a greater concern under dynamic conditions than under static conditions. A static analysis requires consideration of fewer variables than a dynamic analysis and is therefore simpler. The key determinant of steady-state heat flow is thermal *resistance*. An analysis of heat flow under dynamic conditions involves more variables—including thermal *capacitance*. The following discussion begins with steady-state assumptions and then looks at dynamic situations.

Heat flows are of two forms—sensible heat and latent heat. Sensible heat flow results in a change in temperature. Latent heat flow results in a change in moisture content (often humidity of the air). Total heat flow is the sum of sensible and latent heat flows. Materials react differently to sensible and latent heat flows; therefore, the discussion that

TABLE 7.1 Energy, Power, and Heat Terminology[a]

Concept	Terminology	Symbol	Discussion
ENERGY			The term *energy* implies a cumulative perspective, such as the potential for work in a barrel of oil or the solar radiation collected during a heating season.
	British thermal unit	Btu	The British thermal unit is the fundamental I-P unit of energy. A Btu is the amount of energy (heat) required to raise the temperature of 1 lb of water by 1°F. A burning wooden match releases approximately 1 Btu.
	Joule	J	The joule is the fundamental SI unit of energy. A joule is a newton-meter (a force of 1 newton acting over a 1-m distance). A joule is a fairly small unit of energy, so the kilo-joule (kJ), equal to 1000 J, is commonly used in building design.
	Watt-hour	Wh[b]	The watt-hour is a commonly used SI unit of energy (and also applies to I-P electricity consumption). 1 W = 1 J/s 1 Btu = 1.055 kJ 1 kJ = 0.9478 Btu
POWER			The term *power* is used to describe the rate of energy usage, production, or flow. Power is always associated with a time frame (often an hour in building design).
	British thermal unit per hour	Btu/h or Btuh[b]	An I-P unit. Btu/h is used to express heat gains and losses and the design heating and cooling capacity of equipment.
	Watt	W	The watt is the SI unit of power and is used the same as Btu/h. 1 Btu/h = 0.0293 W 1 W = 3.412 Btu/h
	Horsepower	HP	An I-P expression of power, typically used to describe the capacity (size) of certain types of HVAC equipment (such as motors). 1 HP = 2545 Btu/h 1 HP = 746 W
HEAT FLOW			Heat flow is a particular form of power, and in building design is typically expressed in Btu/h or W. Several heat-flow-related properties of materials, with specific definitions and uses, are described herein. These properties are based upon a unit temperature difference.
	Conductivity	k	The rate of heat flow through a unit thickness of a homogeneous (such as wood or brick) material. I-P units: Btu in./h ft^2 °F SI units: W/m °C Btu in./h ft^2 °F × 0.1442 = W/m °C
	Conductance	C	The rate of heat flow through a specific nonhomogeneous object (such as a concrete masonry unit) or a defined thickness of a homogeneous material. I-P units: Btu/h ft^2 °F SI units: W/m^2 °C Btu/h ft^2 °F × 5.678 = W/m^2 °C
	Film or surface conductance	h	The conductance of an air film; same concept and units as conductance.
	Overall coefficient of heat flow	U (or U-factor)	The rate of heat flow through an assembly (window, wall, etc.) bounded by air on both sides. Includes the effects of all materials, air films, and air spaces. I-P units: Btu/h ft^2 °F SI units: W/m^2 °C Btu h ft^2 °F × 5.678 = W/m^2 °C
	Resistance	R	A measure of resistance to heat flow; the reciprocal of conductivity (or conductance). Essentially the force required to cause a unit flow of heat. I-P units: h ft^2 °F/Btu SI units: m^2 °C/W h ft^2 °F/Btu × 0.176 = m^2 °C/W (I-P) R per in. × 6.93 = (SI) R per m
	Permeance	M	Although permeance deals directly with water vapor flow, it is related to heat flow through the need to add or remove heat to humidify or dehumidify a building. I-P units: grains/ft^2 h in. Hg SI units: ng/m^2 s Pa grains/ft^2 h in. Hg × 56.7 = ng/m^2 s Pa

[a]A more extensive listing of I-P (inch-pound) and SI (Système International) units and conversions is provided in Appendix A.

[b]Units oddity: The alternative symbol "Btuh" is shorthand for Btu/h and does not imply a product of energy and time; on the other hand, Wh is a product (1 watt of power over a 1-hr period); furthermore, Btu (without a time unit) is a measure of energy, as is Wh (with a time unit).

follows begins with sensible heat flow and then deals with latent heat flows.

(b) Heat Flow Processes

Whenever an object is at a temperature different from its surroundings, heat flows from the hotter to the colder. Likewise, water vapor flows from areas of greater concentration to areas of lesser concentration. Buildings, like human beings, experience sensible heat loss to and from the environment in three principal ways. *Convection* refers to heat exchanged between a fluid (typically air) and a solid, with the motion of the fluid due to heating or cooling playing a critical role in the extent of heat transfer. *Conduction* refers to heat transferred directly from molecule to molecule, within or between materials, with proximity of molecules (material density) playing a critical role in the extent of heat transfer. *Radiation* refers to heat flows via electromagnetic waves from hotter surfaces to detached, colder ones—even across empty space and potentially great distances. *Evaporation* can also be involved in envelope heat loss, carrying heat away from wet surfaces, but this is less influential for most building designs than for our bodies. Moisture flows through envelope assemblies and via air leakage are the principal means of latent heat gain (or loss).

A combination of sensible heat flow by convection, conduction, and radiation through some typical material assemblies is shown in Fig. 7.6. Heat flow through the various components of a building skin involves both heat flow through solids and heat flow through layers of air. Multiple air spaces and reflective surfaces are useful and inexpensive ways to reduce the flow of heat via radiation when temperature differences are large. Some of the most effective insulating materials, therefore, combine dead-air spaces and layers of reflective films.

(c) Thermal Properties of Components

Each material used in an envelope assembly has fundamental physical properties that determine how that material will affect sensible heat flow. These key properties are described in the following sections.

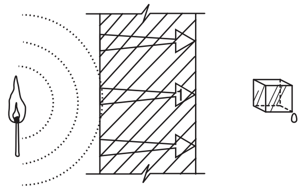
Conductivity. Each material has a characteristic rate at which heat will flow through it. For homogeneous solids this property is called *conductivity* (designated as *k*), and in the inch–pound (I-P) system it is the number of British thermal units per hour (Btu/h) that flow through 1 square foot (ft^2) of material that is 1 in. thick when the temperature difference across that material is 1F° (under conditions of steady heat flow). Thus the I-P units of conductivity are Btu in./h ft^2 °F.

The Système International (SI) equivalent is the number of watts that flow through 1 square meter (m^2) of material 1 m thick when the temperature difference across that material is 1K (equal to 1C°). Thus, the SI units of conductivity are W/m K or W/m °C (these two terms are used interchangeably in the tables related to this chapter).

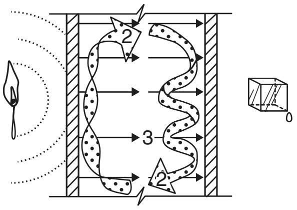
Conductivity is established by laboratory tests and is published as a basic property of homogeneous solids. Conductivity is an important factor in passive heating or cooling designs that depend heavily upon the rate at which heat is conducted into a material from its surface.

Conductance. Many solids such as common brick, wood siding, batt or board insulation, gypsum board, and so on are widely available in standard thicknesses. For such common materials, it is useful to know the rate of heat flow for that standard thickness instead of the rate per inch. *Conductance*, designated as *C*, is the number of Btus per hour that flow through 1 ft^2 of a given thickness of material when the temperature difference is 1F°. The units are Btu/h ft^2 °F. SI units are W/m^2 K. Conductance is also used to describe the rate of heat flow through defined sizes of modular units of nonhomogeneous materials (such as a concrete masonry unit—composed of pockets of air surrounded by concrete).

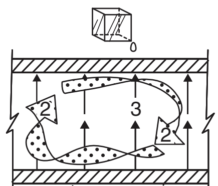
Resistance. Conductivity and conductance are compared in Table 7.1 and Fig. 7.7, which also include another useful property, *resistance*. Designated as R, resistance indicates how effective any material is as an insulator. The reciprocal of conductivity (or conductance), R is measured in *hours* needed for 1 Btu to flow through 1 ft^2 of a given thickness of a material when the temperature difference is 1F°. In the I-P system, the units are h ft^2 °F/Btu. SI units are m^2 K/W. Resistances and other important thermal properties are listed for many conventional building materials in Table E.1 (Appendix E). Table E.2 provides similar information



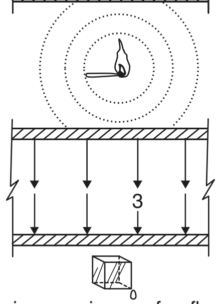
A single solid material illustrates the transfer of heat from the warmer to the cooler side by conduction (1).



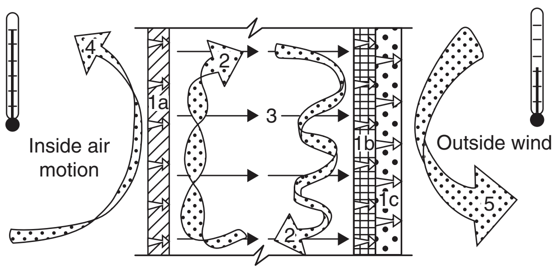
As air is warmed by the warmer side of the air space, it rises. As it falls down along the cooler side, it transfers heat to this surface (2). Radiant energy (3) is transferred from the warmer to the cooler surface. The rate depends upon the relative temperature of the surfaces and upon their emissive and absorptive qualities. Direction is always from the warmer to the cooler surface.



The convective action (2) in the air space of a roof is similar to that in a wall, although the height through which the air rises and falls is usually less. The radiant transfer is up in this case because its direction is always to the cooler surface.



When the higher temperature is at the top of a horizontal air space, the warm air is trapped at the top and, being less dense than the cooler air at the bottom, will not flow down to transfer its heat to the cooler surface. This results in little flow by convection. The radiant transfer in this case is down because that is the direction from the warmer surface to the cooler one.



This example of a wall in place illustrates the several methods by which heat is lost through a composite assembly of materials. Conduction at varying rates in different materials is accounted for in 1a, 1b, and 1c. Convection currents (2) and radiation (3) carry the heat across the air space.

Fig. 7.6 *Heat flow through materials, across air spaces, and through construction assemblies. Means of heat flow include conduction, convection, and radiation.*

for alternative (less commonly used and/or emerging) construction approaches.

Resistance is especially useful when comparing insulating materials, because the greater the R-value, the more effective the insulator. For this purpose, R is sometimes listed as "per inch" of thickness, in which case the units are h ft^2 °F/Btu-in. SI units are m K/W (indicating "per meter" of thickness across 1 m^2, even though the resulting canceling of units looks odd).

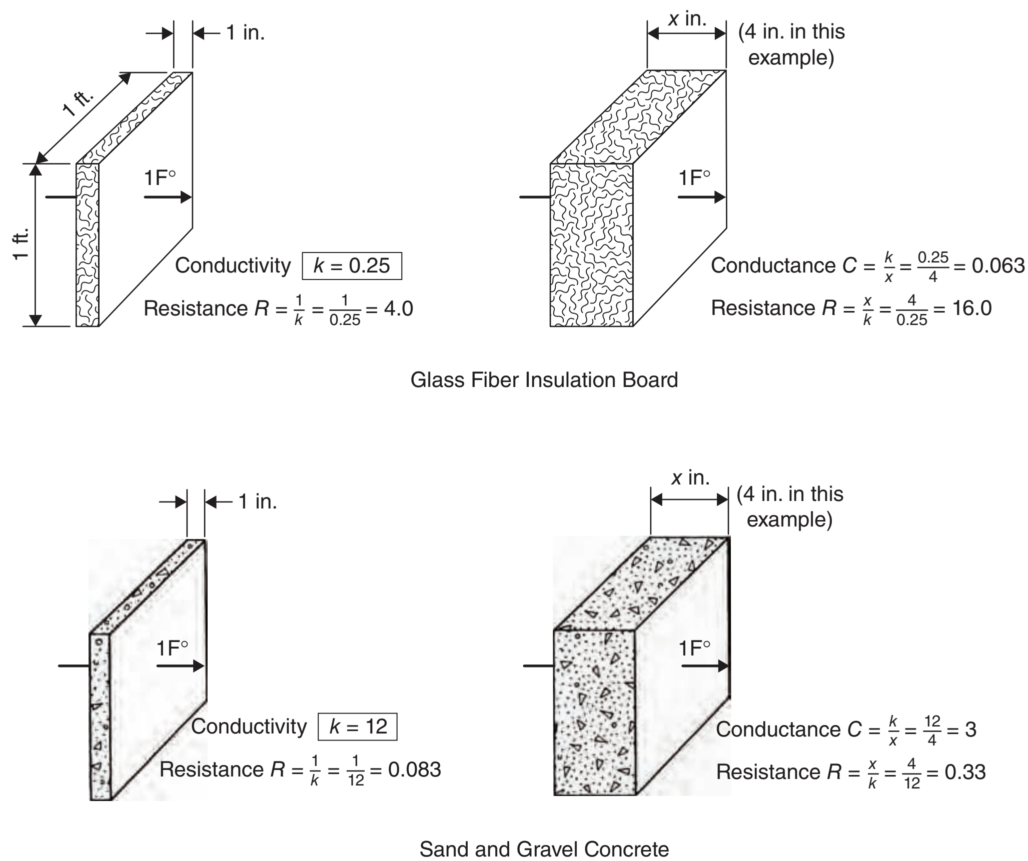


Fig. 7.7 *Relationship between conductivity, conductance, and resistance for two typical materials. Glass fiber is a material of low conductivity (high resistance); concrete is a material of high conductivity (low resistance). Note: Standard unit of area is 1 ft^2 (1 m^2); standard air temperature differential is 1F° (1C°).*

Emittance. Radiation heat transfer is greatly influenced by material surface characteristics; shiny materials are much less able to radiate than commonly used rough building materials. This characteristic is called *emittance*, the *ratio* of the radiation emitted by a given material to that emitted by a blackbody at the same temperature. The impact of emittance (shiny vs. matte surfaces) is seen in Tables E.3, E.4, and E.5, which present properties of air layers and air spaces within construction assemblies; the lower the emittance, the lower the radiative heat exchange. For most materials, emittance is related to absorptance: A highly absorptive (low-reflectance) material will usually have a high emittance as well. *Selective surfaces* (sometimes used in solar collectors) are highly absorptive yet have very low emittance.

(d) Thermal Classifications of Materials

Architectural materials generally interact with heat either as *insulators* that retard the flow of heat (useful for thermal barriers) or as *conductors* that encourage heat flow (useful for thermal storage materials). It is common to find both insulators and conductors in the same construction assembly. For example, a wall can have an inner layer that is highly conductive and thermally massive (for thermal storage), an outer layer that is also highly conductive and thermally massive (for durability and weathering), and a highly insulative, low-mass material in between.

Insulations. Materials used for insulation fall into three broad categories: (1) *inorganic* fibrous or cellular products (such as glass, rock wool, slag wool, perlite, or vermiculite), (2) *organic* fibrous or cellular products (such as cotton, synthetic fibers, cork, foamed rubber, or polystyrene), and (3) *metallic* or metalized organic *reflective* membranes (which must face an air space to be effective).

Insulating materials are available in a wide variety of forms. These include *loose fill* (as might be poured between rafters on the floor of an attic); *insulating cement*, a loose material that is mixed with a binder and troweled onto a surface; and *formed-in-place* materials such as expanded pellets or liquid-fiber mixtures that are poured, frothed, sprayed, or blown into their final locations. Less form-fitting but more common are batts and blankets of *flexible*, *semirigid* insulation, with varying degrees of compressibility and adaptability to substrates. *Rigid* insulation, with little on-site adaptability, is applied in blocks, boards, or sheets and can be preformed to fit nonplanar surfaces such as pipes.

Exterior insulation and finish systems (EIFS) have become popular (and controversial), both for retrofit and for new construction. Utilizing rigid expanded polystyrene boards applied to exterior gypsum, plywood, or cementitious substrates, then covered with fabric-reinforced acrylic, this construction method achieves slightly more than R-4 per inch of thickness (SI: about R-28 per meter).

Reflective materials are available in sheets and rolls of either single or multiple layers, sometimes as preformed shapes with integral air spaces. When used without attachment to blanket or batt insulation, a reflective layer is called a *radiant barrier* and is especially applicable to roofs in warmer climates. Radiant barriers are also useful in east- and west-facing walls in such climates; details of applications in the southern United States are found in Melody (1987).

A combination of dead (still) air spaces and reflective surfaces produces some of the most effective insulating products, especially when assembled of lightweight materials of low conductivity. Glass fiber, cellular glass, expanded styrenes (foamed plastics), and mineral fibers all enclose vast numbers of dead-air spaces per unit volume. When they are bonded to reflective films and properly installed (the shiny film facing a dead-air space), high resistance to heat flow is achieved.

For a summary of contemporary insulation materials, including environmental impacts and life-cycle considerations, see Wilkinson (1999). For a range of information on insulations, see Bynum (2001). *Environmental Building News* published a guide that addresses the environmental impacts of thermal insulations (BuildingGreen.com, 2011).

Conductors. Materials used as conductors are typically dense, durable, and able to readily diffuse heat. Density, conductivity or conductance, and specific heat are important thermal properties for conductors. For a given material, the higher the numerical values of these three characteristics, the more successful that material's performance as a conductor.

Table E.1 lists a variety of thermal properties for many common materials.

Air Films and Air Spaces. Air films and spaces are interesting thermal components. Although they are actually void of material, they possess potentially useful thermal properties and contribute substantially to the insulating capabilities of some construction assemblies. All aboveground envelope assemblies include at least two air films (interior and exterior), and many common assemblies include a substantial air space.

Air Films. At the exposed surface of a solid, heat transfer takes place both by convection and by radiation. Convection is highly dependent upon air motion, so wind speed must be considered when estimating exterior surface convection. Also, because warm air rises and cold air falls, vertical surfaces that encourage natural convection will exchange heat faster than similar surfaces placed horizontally, unless the direction of the heat flow is *upward* through the horizontal layer, as illustrated in Fig. 7.6.

When air motion along a surface is minimal, an *insulating layer* of air attaches itself to the surface. The resistance of this layer of still air along a vertical surface is equivalent to that of a thickness of ½-in. (12.7-mm) plywood. When this air layer is disturbed, however, its resistance drops quickly; with a 15-mph (6.7-m/s) wind, resistance drops to about one-quarter of the still-air value (see Table E.3). Similar drops in air film resistance occur when forced-air registers are located immediately above or below windows.

The insulation value provided by layers of air is often listed as conductance, the reciprocal of resistance. Surface conductances are designated h_i for interior air layers and h_o for exterior or outside air layers (sometimes the symbols f_i and f_o are used instead). Like other conductances, they are expressed in Btu/h ft^2 °F (in SI units, W/m^2 K). The variations in surface resistances and conductances that are typical of building constructions are shown in Table E.3.

Air Spaces. An air space is a planar volume of air contained on two sides by elements (drywall, brick, insulation, etc.) of an envelope assembly. Like the air films just discussed, air spaces can contribute to the overall thermal resistance of a construction assembly. As indicated in Tables E.4 (I-P) and E.5 (SI), the resistance provided by an air space is a function of its width, position (vertical, horizontal, tilted), and surrounding surface emittances. To be effective in resisting heat flow, an air space must be relatively "dead"—without substantial air circulation—a consideration that limits the useful depth of an insulating air space.

(e) Composite Thermal Performance

The variety of terms used to express thermal properties is potentially bewildering. These properties are, however, only components of a larger picture. Fortunately, there is *one* overall property that expresses the steady-state rate at which heat flows through architectural envelope assemblies. This property is the U-factor. U is the overall coefficient of thermal transmittance, expressed in terms of Btu/h ft^2 °F (in SI units, W/m^2 K). U-factors are commonly used to specify envelope thermal design criteria, as presented in Appendix H. Energy codes and standards specify maximum U-factors (or, for insulation alone, minimum R- or maximum C-values) for various components of the envelope. An example of such requirements for a small office is found in Example 7.7. Because U-factors are so important and so often encountered, data for typical wall, floor, roof, door, and window constructions are presented in many design resources (see, for example, Tables E.6 through E.16).

U-factors are calculated for a particular element (roof, wall, etc.) by finding the resistance of each constituent part, including air films and air spaces, then summing these resistances to obtain a total resistance. The U-factor is the reciprocal of this total (Σ) resistance:

$$U = \frac{1}{\sum R}$$

This calculation procedure is shown in Example 7.1. "Precalculated" U-factors for many common constructions are found in Tables E.6 through E.16, typically based upon an outside wind speed of 15 mph (6.7 m/s), except for summer conditions as noted. Unfortunately, architectural creativity often leads to the design of more or less unique enclosure assemblies for which precalculated U-factors cannot be found. U-factor values must then be developed by the design team.

EXAMPLE 7.1 What is the winter U-factor for the wall assembly shown in Fig. 7.8?

SOLUTION

Component	*R (I-P)*	*R (SI)*	*Data Source*
Inside air film	0.68	0.12	Table E.3
Gypsum board (0.375 in. [10 mm])	0.32	0.056	Table E.1
Plastic film vapor retarder	nil	nil	Table E.1
Glass fiber batt insulation (nominal 6 in. [150 mm])	19.00	3.35	Table E.1
Plywood (0.5 in. [12 mm])	0.62	0.11	Table E.1
Wood siding (1 in. [25 mm])	0.79	0.14	Table E.1
Outside air film	0.17	0.03	Table E.3
Total resistance (R)	21.58	3.81	

$$U \text{ (I-P)} = 1/\Sigma R = 1/21.58 = 0.046$$

$$U \text{ (SI)} = 1/\Sigma R = 1/3.81 = 0.262 \quad ■$$

There are several important points to remember about U-factors. The U-factor is a *sensible* heat property—addressing heat flow resulting from a temperature difference but not addressing *latent* (moisture-related) heat flow. The U-factor is an *overall* coefficient of heat transfer, and includes the effects of all elements in an assembly and all sensible modes of heat transfer (conduction, convection, and radiation). The term *U-factor* should be used only where heat flow is from air to air through an envelope assembly. Air-to-ground heat flow (as through a slab-on-grade floor) is a different matter and is considered in Section 7.3(f).

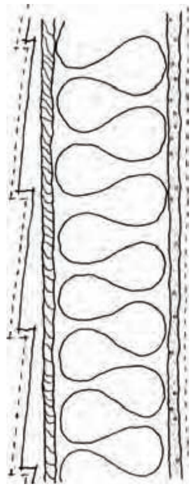


Fig. 7.8 *Wall section used in Example 7.1 to illustrate the process for determining a U-factor (overall thermal transmittance). (Drawing by Jonathan Meendering.)*

Walls. Compared to other elements of the building envelope, wall U-factors are quite straightforward. Ground contact, crawl spaces (as with floors), or intermediary attic spaces (as with roofs) are not present to complicate analysis. There is, however, the issue of thermal bridging. Where framing interrupts an insulation plane, there are two thermally different wall constructions, and a weighted average U-factor (reflecting an insulated wall area paired with a less-insulated wall area) must be found. Example 7.2 illustrates this procedure.

EXAMPLE 7.2 Considering thermal bridging, what is the winter U-factor for the wall assembly shown in Fig. 7.9?

SOLUTION

For those portions of the wall where insulation is encountered:

Component	*R (I-P)*	*R (SI)*
(6) Inside air film (still)	0.68	0.12
(5) Gypsum board (0.5 in. [12 mm])	0.45	0.079
Plastic film vapor retarder	nil	nil
(4) Glass fiber batt insulation (6 in. [150 mm])	19.0	3.32
(3) Vegetable fiber board (0.5 in. [12 mm])	1.32	0.23
(2) Lapped wood siding (0.5 in. [12 mm])	0.81	0.14
(1) Outside air film (15 mph [24 km/h])	0.17	0.03
Total resistance through insulation	22.43	3.92

For those portions of the wall where framing is encountered:

Component	*R (I-P)*	*R (SI)*
(6) Inside air film (still)	0.68	0.12
(5) Gypsum board (0.5 in. [12 mm])	0.45	0.079
Plastic film vapor retarder	nil	nil
(7) Wood studs (nominal 6 in. [150 mm])	6.82	1.20
(3) Vegetable fiber board (0.5 in. [12 mm])	1.32	0.23
(2) Lapped wood siding (0.5 in. [12 mm])	0.81	0.14
(1) Outside air film (15 mph [24 km/h])	0.17	0.03
Total resistance through framing	10.25	1.80

Assuming that 12% of the surface area of the wall consists of framing (studs, sills, and plates), the area-weighted U-factor of the overall wall is as follows:

$R_{insulated} = 22.43$; while $R_{frame} = 10.25$

$U_{insulated} = (1 / 22.43) = 0.045$; while $U_{frame} = (1 / 10.25) = 0.98$

$U_{weighted} = (0.88)\,(0.045) + (0.12)\,(0.98) = 0.158$

The predicted U-factor for the actual wall assembly is thus 0.158 (compared to 1/22.43 = 0.045 if framing is ignored)

SI: $R_{insulated} = 3.92$; while $R_{frame} = 1.80$

SI: $U_{insulated} = (1 / 3.92) = 0.255$; while $U_{frame} = (1 / 1.80) = 0.556$

SI: $U_{weighted} = (0.88)\,(0.255) + (0.12)\,(0.556) = 0.291$ ■

The effects of wood stud framing on wall thermal integrity are quite noticeable. With metal studs, the detrimental effects of thermal bridging are more serious; Table E.8 provides information on correction factors and resulting R-values. The latest editions of ASHRAE Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, and ASHRAE Standard 90.2, *Energy-Efficient Design of Low-Rise Residential Buildings*, present examples of whole-wall U-factors that account for thermal bridging. See Appendix H for excerpts from ASHRAE Standard 90.1.

To illustrate the effects of wall construction and variations in thermal bridging on performance, consider the following range of U-factors, all for nominal 4-in. (100-mm) thick, framed walls with R-13 [SI: R-2.3] insulation located within the stud cavity:

Metal building wall, nominal 4 in. (SI: 100 mm; U = 0.79)	U = 0.14
Steel frame wall, 3.5 in. at 16-in. o.c. (SI: 90 mm at 400-mm o.c.; U = 0.76)	U = 0.134

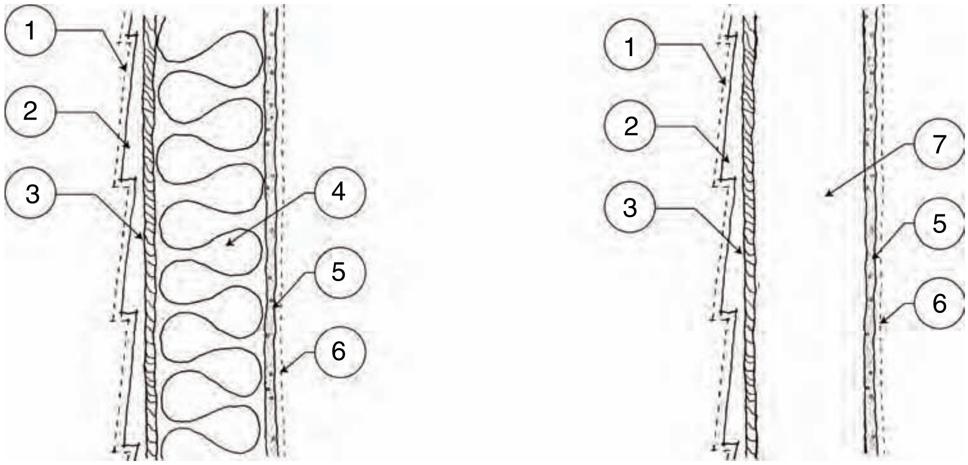


Fig. 7.9 *Wall sections used in Example 7.2 to illustrate the process for determining a weighted-average U-factor to account for thermal bridging in a frame wall. (Drawings by Jonathan Meendering.)*

Steel frame wall, 3.5 in. at 24-in. o.c. U = 0.115
(SI: 90 mm at 600-mm o.c.; U = 0.65)
Wood frame wall, 3.5 in. at 16-in. o.c. U = 0.094
(SI: 90 mm at 400-mm o.c.; U = 0.53)
Wood frame wall, 3.5 in. at 24-in. o.c. U = 0.091
(SI: 90 mm at 600-mm o.c.; U = 0.52)

For a nominal 4-in. (100-mm) wood frame wall, increasing the stud spacing from 16 in. o.c. to 24 in. o.c. (400 mm to 600 mm) decreases (improves) the U-factor from 0.094 to 0.091 (SI: 0.53 to 0.52)—a nominal difference. Changing the framing material from wood to steel studs (at 16 in. o.c.; 400 mm), however, increases (degrades) the U-factor from 0.094 to 0.134 (SI: 0.53 to 0.76)—equivalent to an R-3 (SI: R-0.5) decrease in insulation. The thermal bridging effect of material selections and construction details can make a difference. Mitigating thermal bridges is a key aspect of envelope design for a Passive House project. If a detailed calculation of thermal bridging effects is required, consult the 2013 *ASHRAE Handbook—Fundamentals*, Chapter 25.

Several developments are promising to improve the thermal performance of wall systems. *Structural insulated panels* (SIPs) are available in a wide variety of finishes, sizes, insulation types, and thicknesses. Because a single factory-built panel replaces site-built framing, savings in labor can be substantial. Thermal performance is considerably improved because no framing members penetrate the insulated core. The typical SIP consists of two structural surfaces (often oriented strand board, or OSB) that enclose a core of either expanded polystyrene (EPS: R-4 per inch; SI: R-27.7 per meter) or polyisocyanurate foam (R-6.5 per inch; SI: R-45 per meter). The panels are joined with plywood splines that connect the structural surfaces of adjacent panels in a manner that reduces the thickness of, but does not interrupt, the insulated core. Another joining method, shiplap joints, maintains full-thickness core insulation. Airtightness is generally greater than with stud framing. U-factors of framed walls and SIPs are compared in Table E.9.

Insulated masonry systems can offer lower U-factors while preserving a masonry exterior (for weathering and appearance) and a masonry interior (for thermal mass). Past approaches (filling hollow cores of concrete block or clay tile with insulation) left considerable thermal bridging through the solid masonry, with rather high resulting U-factors. If one of the masonry surfaces is not intended to be exposed, then a continuous layer of insulation can be applied to that face, with much lower resulting whole-wall U-factors. Even in cavity walls, the layer of insulation between wythes of block is usually penetrated by ties—with resulting thermal bridging. The most elementary improvement in this regard uses ties with lower thermal conductivity, such as fiber composite materials in place of steel. Another approach is to use precast blocks that can be stacked integrally with preformed rigid insulation; to the extent that the insulation layer can be both thick and unbroken by ties, thermal bridging is greatly reduced. The following is a sample of manufacturers' whole-wall U-factors for medium-density (120 lb/ft^3 [1920 kg/m^3]) concrete block insulation alternatives:

8-in. two-core concrete block, uninsulated	U = 0.39
(SI: 200-mm two-core concrete block, uninsulated)	U = 2.21
8-in. two-core concrete block with insulated cores	U = 0.19
(SI: 200-mm two-core concrete block with insulated cores)	U = 1.08
8-in. proprietary two-wythe concrete block and core	U = 0.11
(SI: 200-mm proprietary two-wythe concrete block and core)	U = 0.62

Where poured-in-place concrete is not to be used as a surface material, insulating concrete forms (ICFs) can be used to improve thermal performance. This system employs preformed rigid insulation as a formwork for poured concrete; the form/insulation remains in place after the wall is poured. Rigid insulation thus protects both faces of the structural wall (although it isolates the thermal mass); exterior and interior finishes are then applied to the insulation.

Roofs. In the simple case of a roof/ceiling separating a conditioned space from the outdoors, the U-factor is calculated as for walls. Where insulation is broken by framing, the effects of thermal bridging must be considered. Table E.8 shows correction factors to be applied to insulation/metal truss assemblies. Similar adjustments, although of lesser magnitude, are required with wood framing. ASHRAE Standard 90.1 presents several detailed tables of whole-roof U-factors that account for thermal bridging. If a detailed calculation of thermal bridging is required, consult the 2013 *ASHRAE Handbook—Fundamentals*, Chapter 25. Roof insulation, however, is often placed entirely above (or entirely below) the supporting structure, greatly reducing the effects of thermal bridging. There is a growing availability of above-the-roof-structure insulation materials, some penetrated by fastenings, others essentially unbroken. These options should be explored as a means of reducing roof heat loss and gain—with appropriate consideration of the environmental impacts of material selections.

Where an insulated ceiling separates a space from an uninsulated attic, the simplest approach is to assume that the attic is at outdoor temperature. This assumption likely overestimates the winter heat flow rate because the temperature in a vented attic may be higher than the outdoor air temperature—but it simplifies analysis. If an accurate estimate of attic temperature is required, a more complex procedure is used, as presented in the 2013 *ASHRAE Handbook—Fundamentals*, Chapter 27. An attic is a space having an average distance of 1 ft (0.3 m) or more between the ceiling and the underside of the roof. A vented attic is often designed to carry away moisture that may have migrated through the insulated ceiling. See Lstiburek and Carmody (1994) for detailed information on attic design practices.

Floors. When a floor is exposed to outdoor air (as with a cantilever or crawl space), the U-factor is calculated as for walls and roofs. When insulation is placed within framing cavities, the effects of thermal bridging must be included. It is becoming increasingly common to provide a continuous layer of insulation below the framing cavity, thus greatly reducing the detrimental effects of thermal bridging. ASHRAE Standard 90.1 presents several tables of whole-floor U-factors that account for thermal bridging.

Many building codes require vented crawl spaces. In such situations, the simplest procedure is to insulate the floor above the crawl space and assume that the crawl space is at outdoor temperature. This assumption overestimates the heat flow rate, because a vented crawl space will rarely be as cold (warm) as outdoor air under winter (summer) design conditions. If a more accurate analysis of crawl space design temperatures is required, or if crawl space walls are insulated, a more complex procedure is used, as presented in the 2013 *ASHRAE Handbook—Fundamentals*, Chapter 27. It is rarely energy-conserving, however, especially in colder climates, to insulate the walls of a crawl space instead of insulating the floor above. See Lstiburek and Carmody (1994) for detailed information on crawl space design practices.

Doors. Table E.10 lists U-factors for solid (no glazing) doors in common use in North America. These precalculated values are convenient but should be used with care, as air film resistances are a relatively large factor in overall door thermal performance. Many doors are placed near forced-air supply registers or return grilles, reducing the resistance of the indoor air film. Conversely, the exterior air film may be more effective than anticipated because doors are typically protected somewhat by overhangs, porches, and so on. The wind conditions assumed in Table E.10 are typical of winter (not summer) conditions. Where significant door glazing is involved, U-factors should be adjusted to account for the glazing resistance, or data for a specific product should be used.

(f) Special Envelope Heat Flow Conditions

The overall coefficient of heat transfer (U-factor) is a convenient property for analysis of aboveground envelope assemblies. It is only applicable, however, to assemblies exposed to air on both the interior and exterior surfaces. In other situations, such as slab-on-grade floors and belowground walls and floors, U-factor is not a well-defined property (how much soil is part of the floor?), and other thermal analysis methods must be used. Typically, data derived from empirical studies are used in lieu of fundamental heat flow equations. Because the concept of U-factor is so simple to understand and apply, much of the empirical data are presented in terms of equivalent U-factors.

Slab-on-Grade Floors. Heat flow dynamics change when the lower surface of a floor is in direct contact with the ground. The ground is often at a temperature different from that of outdoor air, and earth is more conductive than air. Testing has shown that heat flow in this complex situation is strongly related to slab perimeter length. Table E.11 shows the heat flow rate through a concrete slab-on-grade, given as F_2 units (per foot or meter of perimeter length) rather than U-factors (per unit area). Four edge insulation conditions are shown, with corresponding values of F_2 for three climate zones. Interpolation can be used to estimate F_2 for other climates (correlated to heating degree days). This procedure relates all heat loss from the floor to the length of perimeter.

Slab-on-grade heat loss illustrates the principle of diminishing returns: An incrementally higher R-value does not produce an equally lower heat flow. An insulation truism is that the first few inches (millimeters) of insulation make a much greater impact on the rate of heat flow than do the last few inches (millimeters). Table E.11 lists a maximum slab-edge R-value of 5.4 h ft^2 °F/Btu (SI: R-0.95). If more slab-edge insulation seems desirable, consult Table E.12. Note how much more effective is vertical insulation at the exposed perimeter compared to insulation beneath the slab. The highest F_2 value listed in Table E.12 is for insulation at R-10 (SI: R-1.8) not only around the perimeter, but also under the entire area of the floor slab. This lowest rate of heat flow is a reduction of just 25% from the performance provided by the same insulation employed only around the perimeter to a depth of 4 ft (1.2 m).

EXAMPLE 7.3 A warehouse will be built with a slab-on-grade floor. The warehouse is 80 ft (24.4 m) square in plan. What is the relationship between total slab insulation and rate of heat flow through the slab?

SOLUTION

From Table E.12, F_2 is related to total insulation as follows: building slab perimeter—four sides at 80 ft (24.4 m) each = 320 ft (97.5 m); building slab area: 80 ft (24.4 m) × 80 ft (24.4 m) = 6400 ft^2 (595 m^2).

I-P Units:

Insulation Approach	Total Volume of Slab Insulation Used (ft^3)	F_2 (Btu/h °F)	F_2 × Perimeter = Rate of Heat Flow (Btu/h ft °F)	Reduction in Heat Flow (Btu/h °F)	Reduction per Unit (ft^3) of Insulation
Uninsulated slab	None	0.73	233	None	—
R-5 vertical, 2 ft, 1 in.	(2 ft) (320 ft) (1/12 ft) = 53.3	0.58	186	47	0.88
R-10 vertical, 4 ft, 2 in.	(4 ft) (320 ft) (2/12 ft) = 213.3	0.48	154	32	0.20
R-10 fully insulated, 2 in.	(2 ft) (320 ft) (2/12 ft) + (6400 ft^2) (2/12 ft) = 1173.4	0.36	115	39	0.04

SI Units:

Insulation Approach	Total Volume of Slab Insulation Used (m^3)	F_2 (W/ K)	F_2 × Perimeter = Rate of Heat Flow (W/m K)	Reduction in Heat Flow (W/K)	Reduction per Unit (m^3) of Insulation
Uninsulated slab	None	1.26	123	None	—
R-0.9 vertical, 0.6 m, 25 mm	(0.6 m) (97.8 m) (0.025 m) = 1.5	1.0	97.5	25.5	17.0
R-1.8 vertical, 1.2 m, 50 mm	(1.2 m) (97.8 m) (0.051 m) = 6.0	0.83	80.9	16.6	2.8
R-1.8 fully insulated, 50 mm	(0.6 m) (97.8 m) (0.051 m) + (595 m^2) (0.051 m) = 33.3	0.62	60.5	20.4	0.6

Thus, a minimal initial investment of 640 ft^2 (60 m^2) of 1-in.- (25-mm)-thick insulation cuts the uninsulated slab heat flow by one-fifth. However, a vastly greater investment of 7040 ft^2 (654 m^2) of 2-in.- (50 mm)-thick insulation (22 times as much!) cuts the less-insulated heat flow only by one-fourth. ■

Basements. Heat flow through basement walls and floors is complicated by an increasing length of heat flow path with increasing depth, as shown in Fig 7.10*a* and *b*. A further complication is that the temperature of the earth is not equal to ambient air temperature and becomes more and more out of phase with air temperature at increasing depths. To obtain a "design temperature" for belowground heat loss, first estimate the mean winter temperature of the site location. For example: using Tables C.19 and C.20 in Appendix C, take the average of the ambient temperature (TA) for January and for the year. Then, from this mean winter temperature, subtract the value of the constant amplitude, Fig. 7.10*c*. This gives a design temperature. Table E.13 is then used to determine the heat flow rate.

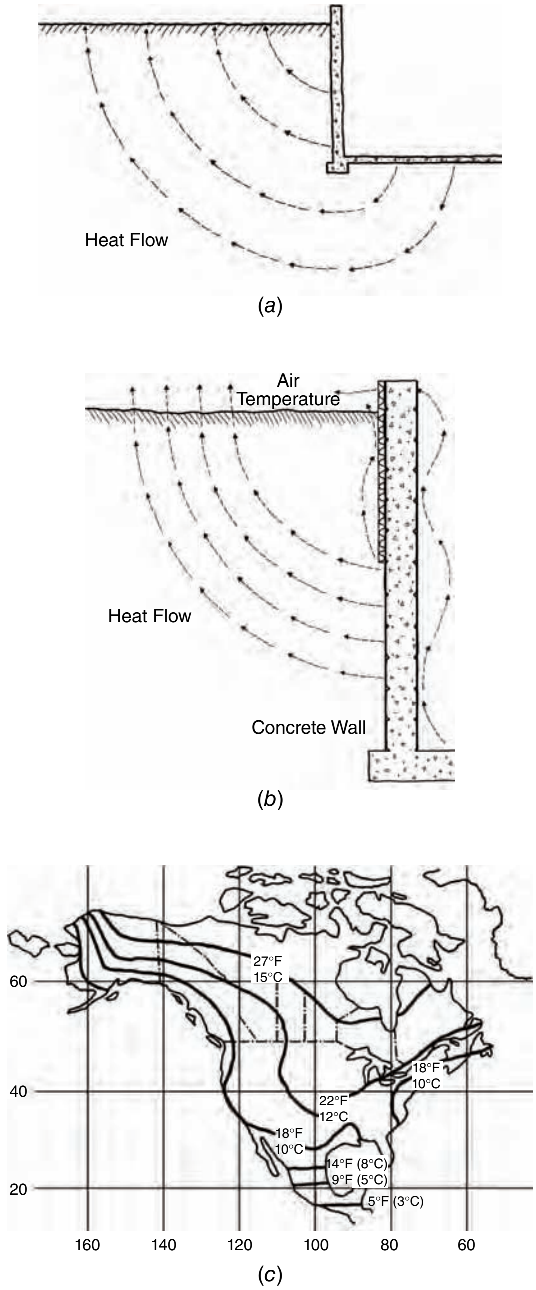


Fig. 7.10 *Heat flow below grade. (a) Heat flow through basement walls and floors follows radial paths (that are generally perpendicular to soil isotherms). (b) Heat flow paths of differing lengths for a partially insulated basement wall. (Reprinted with permission of ASHRAE, from the 2001* ASHRAE Handbook—Fundamentals*; redrawn by Amanda Clegg. This citation to an older version of the* Handbook *is intentional and provides access to historic reference information of ongoing interest.) (c) Lines of constant amplitude of ground temperature; just below the surface, the ground temperature fluctuates around a mean annual temperature by this amplitude. (Reprinted with permission; ©ASHRAE, 2013* ASHRAE Handbook—Fundamentals.*)*

EXAMPLE 7.4 Calculate the design heat loss for a basement in Minneapolis, Minnesota, which is 28 ft (8.5 m) wide by 30 ft (9.1 m) long, sunk 6 ft (1.8 m) below grade. An insulation of R-10 (SI: R-1.8) is applied to this wall to a depth of 2 ft (0.6 m) below grade. An internal temperature of 70°F (21°C) is to be maintained.

SOLUTION

The soil-path design temperature is estimated from Tables C.19 and C.20; for Minneapolis, the TA in January is 12°F (–11°C); TA for the year is 44°F (6.7°C); the average of these is 28°F (–2°C). From Fig. 7.10*c*, the amplitude at Minneapolis is about 24F° degrees (13.3C°). The design temperature at the ground surface is therefore 28 – 24 = 4°F (–2 – –13.3 = –15.3°C).

The heat loss through the basement wall is estimated using Table E.13, Part A, by determining the loss per degree of temperature difference per 1-ft-(0.305-m)-high strip of wall and then summing for the full height of the wall:

1st ft below grade (insulated)	0.080 Btu/h ft °F
SI: 1st 0.3 m: per m height (0.458) (0.305)	= 0.140 W/m K
2nd ft below grade (insulated)	0.075
SI: 2nd 0.3 m: (0.427) (0.305)	= 0.130
3rd ft below grade (uninsulated)	0.273*
SI: 3rd 0.3 m: (1.571) (0.305)	= 0.479*
4th ft below grade (uninsulated)	0.235
SI: 4th 0.3 m: (1.353) (0.305)	= 0.413
5th ft below grade (uninsulated)	0.208
SI: 5th 0.3 m: (1.195) (0.305)	= 0.364
6th ft below grade (uninsulated)	0.187
SI: 6th 0.3 m: (1.075) (0.305)	= 0.328
Total per 6-ft height and 1-ft length of wall	1.058 Btu/h ft °F
Total per 1.8-m height and 1-m length of wall	1.854 W/m K

Basement perimeter = 2 (28 + 30 ft) = 116 ft

SI: 2 (8.5 + 9.1 m) = 35.2 m

Total wall heat loss = 1.058 Btu/h ft °F ×116 ft = 123 Btu/h °F

SI: 1.854 W/m K × 35.2 m = 65.3 W/K

*Note that although this is an increase in loss relative to the segment of wall directly above, it represents a design decision that reflects an understanding of the law of diminishing returns.

The heat loss through the basement floor is calculated using Table E.13, Part B.

Average heat loss per ft^2 floor
= 0.030 Btu/h ft^2 °F (for 28-ft width, 6-ft depth);
SI: per m^2 floor = 0.171 W/m^2 K
(for 8.5-m width, 1.8-m depth)

Floor area = 28 ft × 30 ft = 840 ft^2
SI: area = 8.5 m × 9.1 m = 77.4 m^2

Total floor heat loss = 0.030 Btu/h ft^2 °F × 840 ft^2 = 25 Btu/h °F
SI: 0.171 W/m^2 K × 77.4 m^2 = 13.2 W/K

Total heat loss per degree of temperature difference for the basement below grade: walls 123 + floor 25 = 148 Btu/h °F
SI: walls 65.3 + floor 13.2 = 78.5 W/K

Design temperature difference: (from text above) = 48°F (26.4°C)

Design heat loss below grade = 148 Btu/h °F × 48 °F = 7104 Btu/h
SI: design below-grade heat loss = 78.5 W/K × 26.4 °C or K = 2072 W ■

(g) Predicting Surface Temperatures and Condensation

Surface temperatures, as well as the temperature at any point within a wall, roof, or floor assembly, can be predicted if the indoor and outdoor air temperatures and the thermal properties of the construction are known. (This process is more challenging for belowground assemblies.) The variance in temperature through a cross section of a construction assembly is called a *thermal gradient.* For any construction, the thermal gradient can be predicted by proportioning the collective thermal resistance at any point in the assembly to the overall difference in temperature across the assembly. This procedure is illustrated in Example 7.5.

EXAMPLE 7.5 Determine the thermal gradient, under winter design conditions, through the wall assembly shown in Fig. 7.11. The interior air temperature is 68°F (20°C), and the exterior air temperature is 32°F (0°C).

SOLUTION

I-P Units: Resistance values are from Example 7.1; "reference point" is a shorthand means of describing a series of locations throughout the wall assembly, each on the exterior side of a component; the total temperature gradient spans (68 − 32) = 36°F:

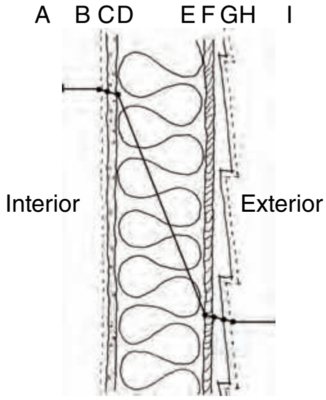
Thermal Component	Component Resistance	Cumulative Resistance	Reference Point	Temperature Difference to Reference Point (°F)	Temperature at Reference Point
Room air	—	—	A	—	68.0
Inside air film	0.68	0.68	B	(0.68/21.58) × (36) = 1.1	66.9
Gypsum board	0.32	1.00	C	(1.00/21.58) × (36) = 1.7	66.3
Vapor retarder	nil	1.00	D	(1.00/21.58) × (36) = 1.7	66.3
Batt insulation	19.00	20.00	E	(20.00/21.58) × (36) = 33.4	34.4
Plywood sheathing	0.62	20.62	F	(20.62/21.58) × (36) = 34.4	33.6
Wood siding	0.79	21.41	G	(21.41/21.58) × (36) = 35.7	32.3
Outside air film	0.17	21.58	H	(21.58/21.58) × (36) = 36	32.0
Outside air	—	—	I	—	32.0

SI Units: Resistance values are from Example 7.1; "reference point" is a shorthand means of describing a series of locations throughout the wall assembly, each on the exterior side of a component; the total temperature gradient spans (20 − 0) = 20°C:

Thermal Component	Component Resistance	Cumulative Resistance	Reference Point	Temperature Difference to Reference Point (°C)	Temperature at Reference Point (°C)
Room air	—	—	A	—	20.0
Inside air film	0.12	0.12	B	(0.12/3.81) × (20) = 0.6	19.4
Gypsum board	0.056	0.18	C	(0.18/3.81) × (20) = 0.9	19.1
Vapor retarder	nil	0.18	D	(0.18/3.81) × (20) = 0.9	19.1
Batt insulation	3.35	3.53	E	(3.53/3.81) × (20) = 18.5	1.5
Plywood sheathing	0.11	3.64	F	(3.64/3.81) × (20) = 19.1	0.9
Wood siding	0.14	3.78	G	(3.78/3.81) × (20) = 19.8	0.2
Outside air film	0.03	3.81	H	(3.81/3.81) × (20) = 20	0.0
Outside air	—	—	I	—	0.0

■

Understanding envelope surface temperatures is fundamental to predicting thermal comfort. How cold in winter, or hot in summer, will an interior surface be, and how will this affect mean radiant temperature? Understanding temperature patterns within materials is critical to establishing where water vapor might condense within or on a wall, roof, or floor assembly; this is discussed further in Section 7.9.



Interactive Animation

Fig. 7.11 *Wall section used in Example 7.5 to illustrate the procedure for calculating a thermal gradient through a construction assembly. (Drawing by Jonathan Meendering.)*

(h) Dynamic Thermal Effects

The preceding discussion of thermal properties of materials and assemblies focused upon static (steady-state) conditions. Such conditions are usually presumed for analysis of winter heat loss (assumed to occur under the darkness of night). A more complex situation exists when thermal conditions experience rapid changes—such as those brought about by solar radiation impinging upon various portions of the building envelope. Dynamic conditions are usually presumed for analysis of summer heat gain (assumed to occur during daylight hours). The dynamic situation requires that the envelope designer consider more thermal properties.

Under static conditions, heat flow is primarily a function of temperature difference (the driving force) and thermal resistance (the mitigating force). Under dynamic conditions, these two factors are still important, but heat storage in the envelope assembly itself becomes a compounding issue. Heat storage is a function of the *density* of a material and its *specific heat*; the product of these two properties is known as *thermal capacity*. Thermal capacity can (but will not always) reduce heat flow via diversion to storage. Heat entering a wall construction during the daytime, for example, can be stored within the wall for several hours until it flows back out to the cool night air—assuming appropriate weather conditions and adequate thermal capacity. As a minimum, the effect of heat entering a massive wall at, say, 10:00 A.M. will not be seen on the interior surface until a few hours later.

Density. Density is the weight of a material per unit volume. In the I-P system, density is given as lb/ft^3; in the SI system, it is given as kg/m^3. For a fixed volume of material, greater density will permit the storage of more heat. Table E.1 provides density data for common building materials.

Specific Heat. Specific heat is a measure of the amount of heat required to raise the temperature of a given mass of material by 1°. In the I-P system, this is expressed as Btu/lb °F; in the SI system, it is expressed as kJ/kg K. It takes less energy input to raise the temperature of a low-specific-heat material than that of a high-specific-heat material. Table E.1 provides values of specific heat for common building materials.

Thermal Capacity. Thermal capacity is an indicator of the ability of a fixed volume of material to store heat. The greater the thermal capacity of a material, the more heat it can store in a given volume per degree of temperature increase. Thermal capacity for a material is obtained by taking the product of density and specific heat; for example:

Thermal capacity for concrete:

$$(140\ lb/ft^3)\ (0.24\ Btu/lb\ °F) = 33.6\ Btu/ft^3\ °F$$
$$SI: (2240\ kg/m^3)\ (1.0\ kJ/kg\ K) = 2240\ kJ/m^3\ K$$

Thermal capacity for water:

$$(62\ lb/ft^3)\ (1.00\ Btu/lb\ °F) = 62.0\ Btu/ft^3\ °F$$
$$SI: (992\ kg/m^3)\ (4.18\ kJ/kg\ K) = 4147\ kJ/m^3\ K$$

Thermal capacity for air:

$$(0.075\ lb/ft^3)\ (0.24\ Btu/lb\ °F) = 0.02\ Btu/ft^3\ °F$$
$$SI: (1.2\ kg/m^3)\ (1.0\ kJ/kg\ K) = 1.2\ kJ/m^3\ K$$

Time Lag. Time lag is a measure of the delay in the flow of a pulse of heat through a material that results from thermal capacity. Units are hours. As an example, if the sun comes out from behind clouds and strikes the exterior surface of a mass wall at 10:00 A.M., the exterior surface temperature will rise quickly. It may be several hours, however, before this temperature "spike" is seen at the inside surface of the wall. The reason is that some heat is being stored in the wall material, and that amount of heat will not continue to flow through the wall. Time lags of several hours are possible with very heavy wall constructions.

Heat storage in a material is similar to the storage of electricity within a capacitor. Thus the term "capacitive insulation." The design effects of capacitive insulation are difficult to analyze without computer assistance. As a result, most hand calculation methods incorporate capacitive effects through the use of surrogate variables that attempt to simplify calculations for the end user. All reasonable computer simulations of heat flow should intrinsically address capacitive effects.

7.4 LATENT HEAT FLOW THROUGH THE OPAQUE ENVELOPE

The information presented in Section 7.3 focused upon sensible heat flow through various elements of the building envelope. Water can also move through building envelope assemblies—in both liquid and vapor states. The focus here is upon water vapor movement (assuming that proper architectural design of the envelope components will control the movement of liquid water). Water vapor will often need to be handled by a climate control system through the use of energy (termed *latent heat*). In the summer, moisture will often (depending upon climate) flow into an air-conditioned building, increasing humidity and requiring dehumidification, which is often accomplished through removal of the latent heat of condensation of the added moisture. In the winter, it is not unusual to add water vapor to the air in a building to keep RH from dropping too low. This is often accomplished by evaporating water by adding the latent heat of vaporization. In some building types and climates, dealing with latent heat may be as big a problem as dealing with sensible heat.

(a) Moisture Control Fundamentals

A difference in *vapor pressure* is the driving force behind moisture flow through components of an intact building envelope assembly, while gaps in the envelope can provide a route for airflow that carries water vapor. Vapor pressure difference is to latent heat flow as temperature difference is to sensible heat flow. The *permeance* of the materials of construction is the latent equivalent of sensible conductance. (As with conductance, *permeance* refers to the bulk properties of a material, and *permeability* refers to unit thickness properties.) The less permeable a material is, the greater the resistance to water vapor flow. Materials with low permeance are termed *vapor retarders*, and are incorporated in envelope constructions as a means of reducing the flow of water vapor and the associated risk of condensation of the vapor within the envelope assembly. I-P units of permeance are grains/h ft^2 in. Hg; SI units are ng/s m^2 Pa. (*Grains* refers to grains of water, with 7000 grains per pound; in. Hg is inches of mercury, a pressure measurement; ng is a nanogram or 10^{-9} of a gram.) The I-P units for vapor pressure are in. Hg; the SI units are Pa (pascals).

From an architectural design perspective, reducing water vapor flow is accomplished using very thin materials (membranes) that must be carefully located to ensure that they work as intended. Although placement within an envelope assembly is critical, vapor retarders take up virtually no space—in drastic contrast to the thickness requirements of sensible heat retarders (insulations). The specific location of a vapor retarder within a wall, roof, or floor cross section will vary with climate and construction types. The fundamental principle, however, is for the retarder to stop the flow of water vapor before the vapor can come in contact with its dew point temperature within the assembly.

(b) Cold Climate Moisture Control

Most common building materials, including gypsum board, concrete, brick, wood, and glass fiber insulation, are easily permeated by moisture. Many surface/finish materials are also permeable. In cold climates, the winter outdoor air contains relatively little moisture, even though the RH may be high. By contrast, indoor air contains much more moisture per unit of volume, despite its probably lower RH. The resulting differential vapor pressure drives the flow of water vapor from high to low vapor pressure (typically from warmer to colder temperature).

The primary problem with water vapor flow in winter occurs when the temperature somewhere within a wall, floor, or roof drops low enough for water vapor passing through the assembly to condense. The temperature at which this occurs is the dew point temperature of the air which is acting as the source for the water vapor. The dew point temperature often occurs within the insulation layer. Insulation can then become wet and thereby less effective, because water conducts heat far better than the air pockets it has filled. If wet insulation compacts, the air pockets are then permanently lost. Worse yet, moisture damage can occur, such as dry rot in wood structural members.

The usual remedy for envelope condensation problems in cold climates is a *vapor retarder* installed within the building envelope assembly. Because very low permeability is desired, these retarders are commonly a plastic film installed with as few gaps and holes as possible. Because the moister air on the warm side of the envelope is the source of the problem, the vapor retarder needs to be installed *as close to the warm side as possible*—typically, just behind the interior surface (gypsum board, wood flooring, etc.) before the dew point can be encountered by wandering water vapor. With the use of higher insulation R-values, however, installing the vapor retarder within the insulation at a point about one-third of the distance from the interior to the exterior is becoming common. This allows the inner one-third of the wall to be used as a chase for wiring or plumbing without penetrating the retarder, yet with enough insulation beyond this point to prevent condensation by maintaining the temperature above the dew point.

Another approach is to use vinyl wallpaper or vapor retarder paints on interior surfaces of the envelope. These give less protection, however, than the around-the-corners wrap that can be achieved with properly installed plastic films. This performance disadvantage is shared by aluminum-foil-faced insulation; it is very effective thermally but less effective as a vapor retarder. Also, the aluminum foil must face an air space if it is to be thermally effective as a radiant barrier.

A substantial benefit of plastic films is that they also reduce airflow through construction—acting as an air barrier. Outdoor air is always infiltrating a building, gradually replacing the indoor air. This unintended flow of cold air becomes a problem when temperatures outside are very different from those inside, especially when strong winds force outdoor air indoors fast enough to produce noticeably cold drafts. Therefore, the combined moisture-blocking and infiltration-blocking characteristics of plastic film vapor retarders are usually beneficial.

In cold climates, condensation on cold interior surfaces can also occur, especially at windows (with little resistance to reduce the slope of the thermal gradient). Occupant annoyance or material damage can result. Although the air indoors may not be particularly humid (perhaps 30% to 50% RH), it often contains enough moisture to support condensation on cold surfaces. Condensation can be readily predicted (see Fig. 7.11) and addressed during design. Historically, warm air was introduced near a cold glass surface to reduce condensation potential and increase mean radiant temperature. Strategically placed air registers/diffusers and baseboard radiators were commonly used tools. This approach carries an energy burden, however, as heat loss through the glazing is increased via an increased delta *t* and decreased R-value. Better glazing is recommended as an environmentally preferred solution.

(c) Hot, Humid Climate Moisture Control

In hot, humid conditions, cool surfaces are often encountered inside a building—for example, a radiant cooling panel, a chilled water pipe, or a supply air diffuser. If hot, humid air contacts such a surface, condensation can occur—with the moisture vapor in the air condensing to form visible droplets of water on the cool surface. The result can be mildly annoying if droplets of condensation fall on occupants, or serious if water stains occur and, eventually, mold grows on damp surfaces.

In hot, humid climates, the object is to keep the moisture in the warmer outdoor air from penetrating to the cooler (and usually less humid) interior. One method is to use a *drainage plane*, installed just inside the exterior surface material, to block the flow of liquid water through the envelope. The drainage plane can consist of simple tar paper (building felt) and an air space. If any moisture succeeds in penetrating this drainage plane, it should be allowed to wick to the interior; therefore, no vapor retarder (such as plastic, vinyl wallpaper, or vapor retarder paints) should be used on interior surfaces. Numerous severe problems with water vapor damage to building interiors—and related mold and mildew growth, with associated IAQ problems—have been publicized, typically related to condensation of moisture on the exterior-facing (hidden) side of vinyl wall coverings used as an interior finish. See Lstiburek and Carmody (1994) for details on hot and cold climate moisture control.

7.5 HEAT FLOW THROUGH TRANSPARENT/TRANSLUCENT ELEMENTS

Heat flow through windows and skylights requires special attention for several reasons. Despite dramatic improvements, these transparent/translucent envelope components still usually have the lowest R (highest U) of all components in an envelope. Also, they are major contributors to infiltration of outdoor air, which adds to winter heating or summer cooling loads. Perhaps thermally most important, they admit solar heat, for better (winter, in envelope-load-dominated buildings) or worse (summer, in all buildings in most climates). Windows and skylights are designed to allow solar radiation (heat) to pass with minimal resistance, unlike the opaque elements discussed in Section 7.4. Transparent/translucent devices also admit daylight to buildings and often provide desired ventilation. The variety of such components and the several important roles they play require special attention from designers.

A standardized approach to rating window performance characteristics has been developed in North America. This approach is coordinated by the National Fenestration Rating Council (NFRC). Each certified window or skylight bears an NFRC label verifying that the window has been independently rated. The label carries a brief description of the product, such as "Model #, Casement, Low-e = 0.2, 0.5″ gap, Argon Filled," and lists the following performance information: U-factor, solar heat gain coefficient (SHGC), and visible light transmittance (VT). Figure 7.12 shows a sample NFRC label. Similar labels are available for site-assembled window units. Characteristics of some residential-sized windows are found in Table E.15.

The following sections provide information on fundamental thermal properties of transparent/translucent assemblies and approaches that can be

Fig. 7.12 *Certifying window thermal performance; a sample NFRC window label. (© National Fenestration Rating Council; used with permission.)*

taken to enhance the performance of such assemblies. A transparent material permits a generally undistorted view (as with clear glass); a translucent material permits at best a distorted view (as with glass blocks or milky plastic). Both types of material, however, permit some unimpeded transmission of radiation—as opposed to an opaque material/assembly that permits no direct solar radiation transfer.

(a) U-factor

As with opaque envelope components, heat flow due to temperature differences through windows and skylights is a function of the U-factor. The determination of U-factors for windows and skylights is complicated by significant differences in heat flow rates between the center-of-glass, edge-of-glass, and frame portions of a unit. The NFRC "U-factor" melds these into a single representative value for an entire window or skylight unit. The size of the air gap between glazing panes, the coatings on the glazing panes, the gas fill used between glazing panes, and the frame construction all influence the U-factor. The lower the U-factor, the lower the heat flow for a given temperature difference. Tables E.14, E.15, and E.16 list U-factors for various windows and skylights. Appendix H presents sample requirements for window U-factors and SHGC (solar heat gain coefficient, see Section 7.5*b*) for nonresidential buildings (these have been excerpted from ASHRAE Standard 90.1).

(b) Solar Heat Gain Coefficient (SHGC)

This thermal property is also generally based upon the performance of the entire glazing unit, not just that of the glass portion. SHGC represents the percentage of solar radiation (across the spectrum) incident upon a given window or skylight assembly that ends up in a building as heat. It is a measure of the ability of a window to resist heat gain from solar radiation. SHGC can theoretically range from 0 to 1, with 1 representing no resistance and 0 representing total resistance. SHGC values for real products typically range from about 0.9 to 0.2. SHGC is dimensionless. A high SHGC (meaning poor resistance to radiant gain) is desirable for solar heating applications, whereas a lower SHGC (good resistance) is better for windows where cooling is the dominant thermal issue. Solar heat gain coefficient depends upon the type of glass and the number of panes, as well as tinting, reflective coatings, and shading by the window or skylight frame.

NFRC tests and lists SHGC values only for glazing units; ratings do not include auxiliary elements such as draperies, overhangs, trees, and the like. Prior to the development of the SHGC approach, the term *shading coefficient* (SC) was universally used to quantify the same concept. Shading coefficients, however, were based only upon the glass portion of a glazing unit—specifically excluding the frame. Although theoretical SC values also range from 0 to 1, the basis of SC is different from that of SHGC. SC is the ratio of radiant heat gain through a given type of glass relative to 1/8-in.- (3-mm)-thick single clear glass. SC is still a useful concept for comparing glass types and especially for expressing the effects of external or internal shading devices. Procedures for merging SC and SHGC values have not really been formalized.

A wide variety of window and skylight U-factor, SHGC, and VT (see Section 7.5*c*) data can be found in Chapter 15 of the 2013 *ASHRAE Handbook—Fundamentals*. Tables E.17 through E.24 list SHGC, SC, and/or VT values for various types of transparent/translucent products and shading approaches.

A small sample of U-factors for skylights is shown in Table E.16. Note in this table the great thermal penalty paid when using smaller units; the "manufactured skylights" are 2 ft × 4 ft (600 mm × 1200 mm), whereas the "site-assembled glazing" unit size is 4 ft (1200 mm) square. For otherwise identical construction, the whole-component U-factors are almost twice as high for the smaller units. With these smaller units, a frame with better thermal performance is a smart investment.

(c) Visible Transmittance (VT)

This thermal/optical property represents the percentage of incident light (only the visible spectrum) at a normal angle of incidence that passes through a particular glazing. VT is dimensionless. The higher the visible transmittance, the greater the daylight transmission. VT is influenced by the color of the glass (clear glass has the highest VT) as well as by coatings and the number of glazings. VT may be expressed relative to the glass portion only of a glazing unit or relative to the glass and frame. The appropriate expression will depend upon the nature of an analysis; in any case, noncomparable values should not be compared. All NFRC-certified VT values should be directly comparable.

It might seem intuitive that any glazing or coating that reduces SHGC (via lower radiation transmission) will also reduce VT (implying lower radiation transmission). This is not always the case, however, because SHGC deals with the full solar radiation spectrum (including light), whereas VT deals only with the visible (light) spectrum. Spectrally selective glazings and selective coatings can greatly reduce SHGC with little reduction in VT. The relationship between SHGC and VT is expressed as the *light-to-solar gain ratio* (LSG), obtained by dividing the VT by the SHGC. The greater the LSG, the more suitable a glazing is for daylighting in hot climates (or wherever cooling is the dominant thermal condition). Values of LSG are not listed on NFRC labels. LSG values for common glazing units (including the effects of the frame) are included in Table E.15.

(d) Air Leakage

This is the rate of outdoor air infiltration between a new window and its frame measured under defined conditions—usually under pressure equivalent to that of a 25-mph (40-km/h) wind, with the window locked. *High-performance* windows may be tested/rated at even higher pressures. As weatherstripping deteriorates with age, higher rates of infiltration may be expected with older and well-used windows. Design air leakage values are not required to be listed on NFRC labels but may be obtained from manufacturers' catalog data.

(e) Low-Emittance (low-ε) Coatings

These coatings are typically applied to one glass surface facing into the air gap between multiple glazings. A low-ε coating blocks a great deal of the radiant transfer between the glazing panes, reducing the overall flow of heat through the window and thus improving the U-factor. Indeed, one such coating is almost as effective as adding another layer of glazing. In Table E.15, compare the U-factor for window 5 with the U-factors for windows 7 and 12. An important added benefit of these films is their reduction of UV transmission, thus reducing fading of objects and surface finishes in rooms.

Two approaches to providing low-ε films are *hard-coat* (durable, less expensive, but less thermally effective) and *soft-coat* (better thermal performance but more expensive and subject to degradation by oxidation in the manufacturing stage).

Three common types of low-ε coatings are:

1. *High-transmission low-ε.* For passive solar heating applications, where a low U-factor is combined with a high SHGC; window 7 in Table E.15 is an example. The coating is on the inner glazing, where it traps outgoing infrared radiation that otherwise would be lost. Summer overheating can be avoided with external shading devices.
2. *Selective-transmission low-ε.* Where winter heating and summer cooling are both important, requiring low U-factor and low SHGC, but with a relatively high VT for daylighting. Window 9 in Table E.15 is an example, with an LSG ratio of 1.65. The coating is on the outer glazing, where it blocks incoming infrared radiation, which as heat is then convected away by outdoor air.
3. *Low-transmission low-ε.* Where the sun is the enemy, low U-factor, low SHGC, and even low VT seem warranted. Window 10 in Table E.15 is an example, again with the coating on the outer glazing, where it rejects more of the solar gain. With a tinted exterior glazing, even lower SHGC and VT could result.

(f) Selective Transmission Films

Heat flow due to radiation can be greatly reduced by the introduction of a selective transmitter (or *low-emittance*) film somewhere within the glazing cavity. As shown in Fig. 7.13, these films admit most of the incoming solar radiation in both the visible and near-infrared (short) wavelengths. Warm objects within a room emit far-infrared (long-wave) radiation. This long-wave radiation is reflected back into the room by the selective film. These selective films typically are available as separate sheets that can be inserted between sheets of glazing as a window is fabricated. As a separate sheet, a selective film could also be applied to existing windows—for instance, between storm windows and the ordinary windows they protect.

With continuing advances in glazing performance, an increasing range of selective transmission options is available. For example, products from

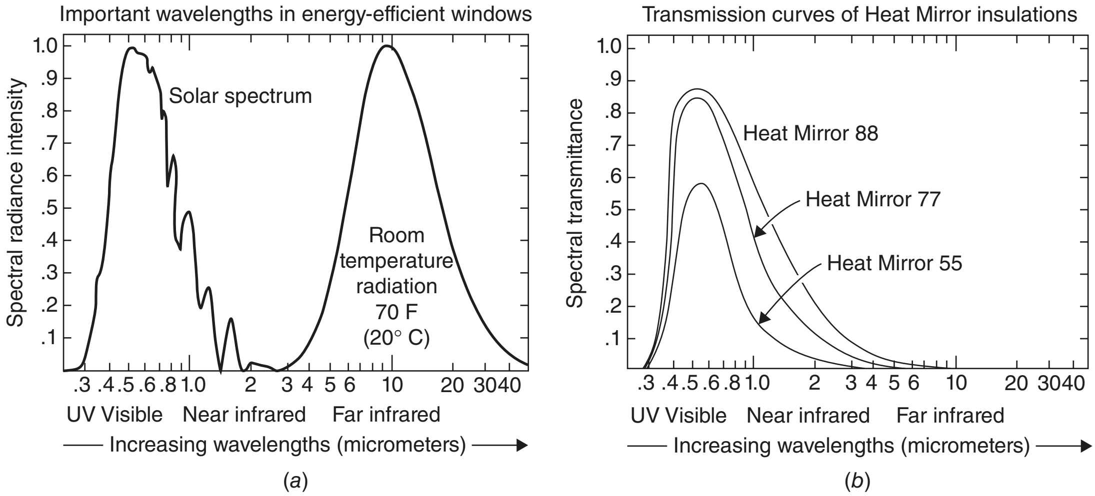


Fig. 7.13 *Performance of selective transmitters. (a) Spectral characteristics of solar (short-wavelength) radiation and room-temperature (long-wavelength) radiation. (b) Transmission and reflection performance for several Heat Mirror selective transmitter films. Incoming solar radiation (both visible and near-infrared) is mostly transmitted, whereas heat radiated from room-temperature objects is reflected and thereby kept within heated spaces. (Courtesy of Southwall Corporation.)*

Southwall Technologies range from Heat Mirror 77 (low reflectance, recommended for vertical glass) to Heat Mirror 22 (low transmission, recommended for sloping glass), and provide various colors. A clear Heat Mirror 88 has the lowest reflectance of all. Some skylight and greenhouse manufacturers offer this low-emittance product as a standard option.

(g) Inert Gas in the Air Gap

Filling an enclosed air space with argon or krypton has thermal benefits. These less-conductive gasses greatly reduce heat transfer by convective currents within the air gap between multiple glazing panes, producing lower U-factors. As a result, the inner surface of the glass is maintained at a temperature closer to that of the indoors, with greater comfort (because radiant heat flow to or from the window surface is reduced) and less chance of condensation on the inside surface. To preserve this gas fill over the life of the window, a very reliable edge seal is required.

For argon, the optimum gap width is about ½ in. (12 mm). When a thinner window is needed, more expensive krypton can be used with a gap of only ¼ in. (6 mm). Because the combination of inert gas and low-ε coatings is so effective at lowering the U-factor, most manufacturers offer them together (as with windows 7 through 11 in Table E.15) rather than separately.

(h) Superwindows

When the available high-performance glazing options are combined in one product, it is called a *superwindow*. The combination of multiple glazing panes and/or suspended films, coatings, inert gas fill, and sealed/thermally broken frame construction yields a lower heat flow rate and a higher price. Window 11 in Table E.15 is a superwindow. An early example of a superwindow is shown in Fig. 7.14: a double-glazed assembly with two selective films, yielding three gas-filled cavities. With a combination of superior thermal resistance and useful solar gain potential, superwindows can conceivably provide *better* heating-season thermal performance than an insulated opaque wall. The potential design consequences are enormous. Figure 7.15 compares the heating- and cooling-season performance, in a residential application, of several windows in three U.S. locations with quite different climates.

(i) Shading

Perhaps the single most important energy-related component for passively cooled buildings is a shading device. Because solar-heated buildings will

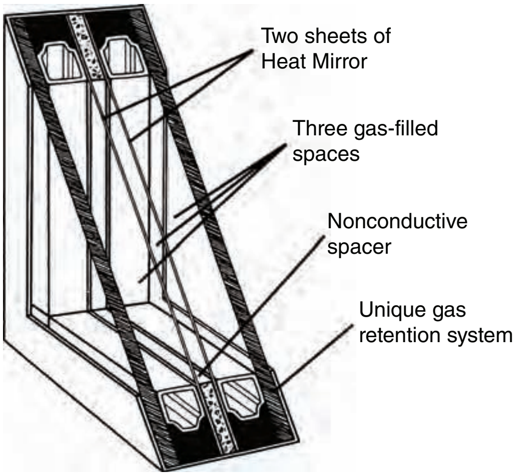


Fig. 7.14 *The Superglass window system (an early superwindow) utilized two Heat Mirror films between two outer panes of glass. Three air spaces are thus created and filled with a nonreactive gas mixture to retard convection. Nonmetallic spacers reduce heat flow at window edges. The resulting window provided a center-of-glass insulating value of R-8.1 (SI: R-1.43). Very low transmission of UV radiation is another characteristic. (Courtesy of Hurd Millwork Company, Medford, WI.)*

often experience overheating in hot weather, sunshading is critical for passively heated buildings as well. When correctly implemented, sunshading can reject most unwanted solar heat gain while helping distribute daylight deep into buildings, thus reducing internal heat gains caused by electric lighting.

If a building is arranged to intercept the intense rays of the sun *before* they pass through its transparent envelope elements, instead of afterward, the cooling load can often be cut in half. In general terms, effective external shading rejects about 80% of solar energy, whereas internal shading absorbs and reradiates 80% of it. Outside louvers have a chance to cool off in an occasional breeze, but inside draperies are part of a heat trap, and they constitute a system of hot-weather heating that causes discomfort for those who work near perimeter surfaces.

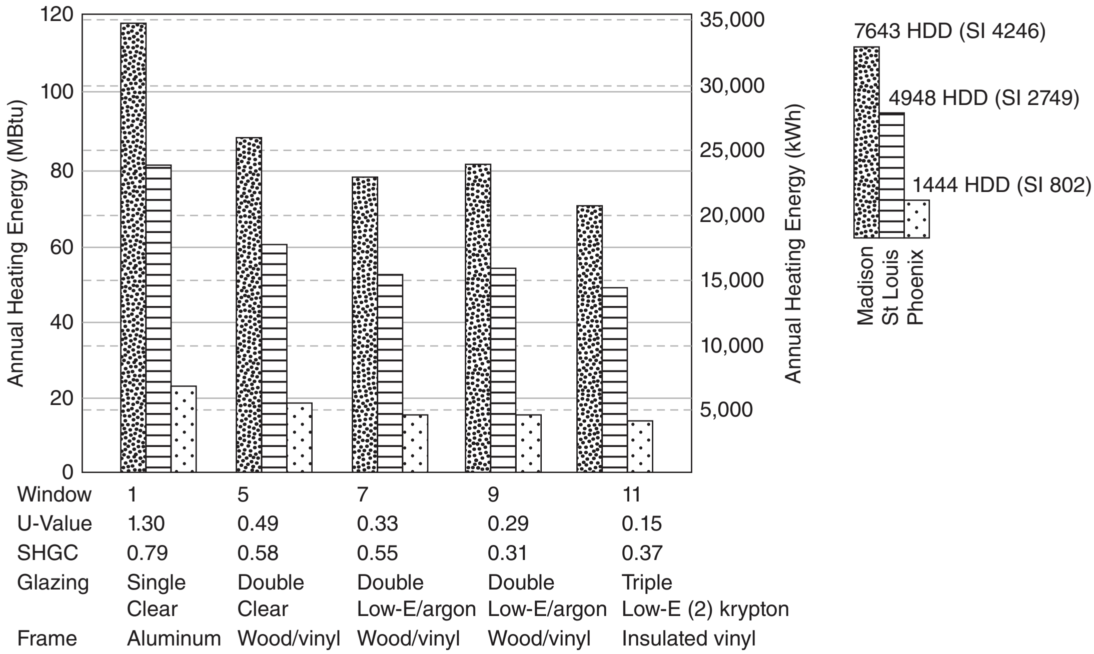
To properly reject direct sun yet allow for a view and daylight, many sunshades project out from the windows they protect. These exterior projections become highly visible elements of façades, and they tempt some designers to impose formal aesthetic criteria that can be damaging to the solar control functions. A frequent example is the application of the same sunshade geometry to all façades of a building. When the sunshades are fixed in position, this tends to help one façade but not the others (see Fig. 3.19). Where they are movable, as with awnings, such a façade-indifferent sunshade approach is not so serious.

Fixed sunshading devices are very common, partly because they lack moving parts and controls that can be expensive and troublesome. They pose a dilemma in the spring and fall, however, because in order to block the sun on any elevation in September, they will also block it in March. For many buildings in temperate climates, March is a heating-need month, whereas September is a cooling-need month. A procedure for evaluating fixed shading device performance is presented in Chapter 6; some approximate shading effects, expressed as shading coefficients, are found in Tables E.20 and E.21.

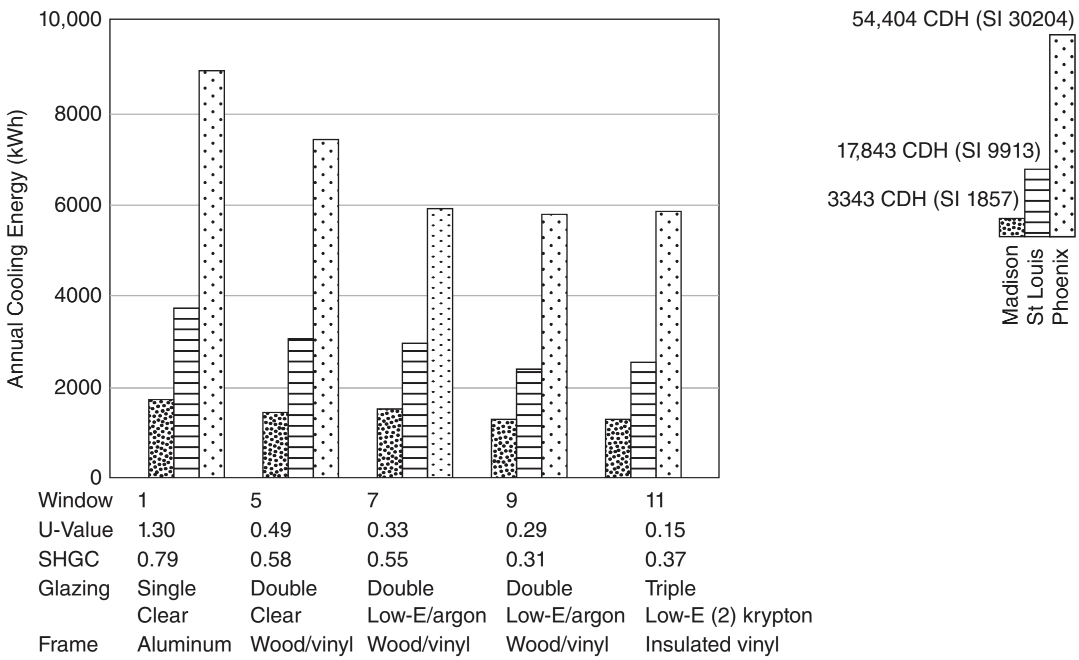
Adjustable sunshading, once extremely common (it seemed that every 1930s shop and office window had an awning) but later considered old-fashioned, has made a comeback with an increased interest in passive systems. Some basic approaches to adjustable shading devices are shown in Table E.22. The first type shown, made of durable materials, has proved effective against both break-ins and hurricanes.

How are movable shading devices adjusted to the desired position? Most manufacturers offer three types of controls: manual, motorized, and automatic. Manual systems are cheap and relatively trouble-free, but they require thoughtful, timely action by the users of a building. So do motorized controls, but for adjusting large/heavy devices in remote places (clerestories, for example), motorized assistance is a practical necessity. Automatic systems have the advantages of freeing the users from adjustment tasks and of taking into account the thermal needs of the building as a whole when setting the sunshade's position. With computerized controls now commonplace for large buildings, the added costs of controls for automatic sunshading can easily be incorporated into the overall cost of controls.

Interior shading devices are less effective than exterior devices but are far more commonly used. There are several reasons for this seeming contradiction. They are not subject to weathering or dirt accumulation and generally are easier for users to adjust. The designer who prefers a clean, apparently unchanging façade appearance will rely on



(*a*) Heating season



(*b*) Cooling season

Fig. 7.15 *(a, b) Seasonal energy performance comparison of various windows—assuming a typical 1540-ft² (143-m²) residence with a glazing area of 15% of the floor area, equal glazing area on all four orientations, and no external or internal shading. Window numbers correspond to those in Table E.15. MBtu = million Btu; HDD = heating degree days, base 65°F (18.3°C); CDH = cooling degree hours, base 74°F (23.3°C). U-factors in figure are I-P values; multiply these by 5.678 for SI U-factors. (From* Residential Windows: A Guide to New Technologies and Energy Performance*, by John Carmody, Stephen Selkowitz, and Lisa Heschong. Copyright © 1996 by John Carmody, Stephen Selkowitz, and Lisa Heschong. Adapted by permission of W. W. Norton & Company, New York.)*

interior devices—often at substantial energy cost. Tables E.23 and E.24 list shading coefficients for several combinations of interior shading devices.

The overall performance of multiple shading devices/approaches can be estimated by taking the product of the shading coefficients for individual devices that are used in series. For example, the overall shading coefficient of a window with external shading with an SC of 0.75, integral shading from the glazing unit of 0.65, and internal shading providing an SC of 0.7 is (0.75) (0.65) (0.7) = 0.34. In general, shading coefficients lower than 0.2 should be included in energy analyses with caution. There is no direct conversion between SHGC values and SC. Nevertheless, it may be necessary to convert an SHGC value to SC in order to determine the overall shading performance of a glazing unit with external or internal shading devices. In this case, an approximate conversion of SC = SHGC/0.87 may be used.

7.6 TRENDS IN ENVELOPE THERMAL PERFORMANCE

There have been huge increases in installed component R (therefore, huge decreases in assembly U-factor) over the past 30-plus years. Sometimes this has occurred because of the use of increased thicknesses of insulation (as with many current wall and roof designs), sometimes because of substantially changed materials (as with windows). Improvements in code minimum values for envelope performance at times seem painfully slow to emerge, especially in light of growing concern for climate change mitigation and green design initiatives. Publication of the *Advanced Energy Design Guide* series (ASHRAE) has been a welcome addition to the designer's tool kit. Although not mandatory, these guides (dealing with a range of building types and currently setting two levels of substantially improved building energy performance) suggest easy-to-adopt ways to reduce building energy consumption—including improvements in envelope performance

What might the next quarter-century bring, and how might the designer of today's building envelopes anticipate—or participate in—these advances?

Smaller-building structural systems may be changing due to the advent of SIP. "May be" was intentionally used in the previous sentence; diffusion of innovations through the complex building industry is a generally slow process. Structural insulated panels promise greatly improved insulation and airtightness compared to the site-assembled wood or steel framing systems they would replace. SIP can incorporate the latest developments in both insulated cores and thermal storage surfaces, and do so with less thickness and lighter weight than stick-built alternatives. Since the early 1970s, walls have progressed from using R-7 (SI: R-1.23) batts between typical 2-in. × 4-in. (50-mm × 100-mm) studs to R-26 (SI: R-4.58) batts between 2-in. × 6-in. (50-mm × 150-mm) studs plus insulating sheathing, thereby providing a threefold reduction in heat flow. With R-values for production SIPs now ranging from R-15 to R-60 (SI: R-2.7 to R-10.5), serious envelope performance is readily available. Another development is an interior panel surface of phase-change wallboard, to store and release heat at room temperatures. This could increase thermal capacity considerably with very little increase in weight, with advantages for winter solar heating and summer night ventilation. Floors and roofs can similarly benefit from the use of SIP rather than framed construction.

Insulation developments include aerogel, gas-filled panels, powder-evacuated panels, and compact vacuum. Some of these products are suitable for retrofit applications in existing construction. Aerogel is both transparent and porous, one of the lightest solid materials. Silica aerogel can be foamed into cavities without ozone-depleting CFCs. In a 90% vacuum, silica aerogel has a resistance of R-20 per inch (SI: R-139 per meter). By adding carbon to absorb infrared radiation, R-32 per inch (SI: R-222 per meter) is possible.

Gas-filled panels are hermetically sealed plastic bags enclosing honeycomb baffles of thin polymer films and low-conductivity gas (argon, krypton, or xenon). Relative resistance values of these insulating cores are: argon, R-5.2 per inch; krypton, R-13.4 per inch; and xenon, R-19.3 per inch (SI: R-36, 93, and 134 per meter, respectively). Powder-evacuated panels contain a vacuum and compacted silica-based powder sealed within a multilayer gas barrier. Expensive to produce and threatened by punctures, this may be a development more suited for appliances than for buildings. The resistance is about R-20 to R-25 per inch (SI: R-139 to R-173 per meter).

Windows have undergone the most dramatic thermal improvement. Resistances for window units (glazing plus frame) have evolved from about R-1 (SI: R-0.18) to R-6.5 (SI: R-1.14) and higher. Prototypes as high as R-20 (SI: R-3.52) exist. Such improvement has been accomplished through a series of developments: a second layer of glass; a wider air space between glazing layers; tinted, reflective, photochromic, and low-emissivity coatings; low-conductivity gas between glazings; intermediate films between glazings; operable blinds between glazings; lower-conductivity glazing spacers and frames; and more airtight weather-stripping. Future developments are likely to include *smart windows* with on-demand variable light transmission. For example, in electrochromic glazing an applied electric field switches the window from a clear state to one with a deep coloration; intermediate states of coloration are possible. The most likely application is in cooling-dominated climates where control of glare, solar gain, and visual privacy are paramount. The net-zero energy Research Support Facility at the National Renewable Energy Laboratory in Golden, CO, employed an area of such glazing (NREL 2013). Carmody et al. (1996) provide an excellent overview of residential window technologies, while Carmody et al. (2003) provide a similar overview of commercial window technologies.

Windows do so many things in addition to providing weather protection—admitting daylight, allowing views outdoors and in, admitting breezes, and admitting warming winter sun—that their relative thermal weakness compared to their desirability continues to challenge building designers. Over the next quarter-century, windows may well continue to display the most dramatically improved resistance to heat flow of all the components of the envelope.

Roofs are of particular interest relative to heat gains and losses because they are subjected to such extreme conditions. On a clear night, radiant losses to the sky can lower a roof's surface temperature below that of the outdoor air—beneficial in summer, but a problem in winter. In summer, elevated roof surface temperatures in sunlight are dramatic and problematic. Efforts are under way to disseminate information regarding the benefits of *cool roofs* and to incorporate credit for such roofs into national energy codes (CRRC, 2013). Both reflective roofs and green (or eco-roof) designs are being employed.

Windows historically represented the component with the greatest heat flow rate in a typical building envelope. Today, the highest rate of heat flow is more likely to be from outdoor air infiltration (or deliberate ventilation). As will be discussed in Section 7.7, limiting heat flow via unwanted air movement is an important aspect of envelope design. The tightness of buildings has improved remarkably over the past 20 years, partly due to improved components (such as windows) and partly due to increased care in construction (involving caulking and air barriers/retarders). As a result of this radical improvement, building airtightness as a means of reducing energy usage is now in conflict with IAQ needs and concerns. It is likely that future improvements in this area will revolve around the use of heat recovery ventilators that permit reasonable ventilation rates without excessive energy penalties.

Commissioning of the building envelope is a rapidly emerging trend. Commissioning goes beyond construction quality control to attempt to ensure (through design review, documentation, and testing) that envelope design, construction, and maintenance meet the owner's project requirements. The National Institute of Building Sciences developed a building envelope commissioning guideline that is currently available via the *Whole Building Design Guide* (NIBS, 2012).

Thinking outside of the box, *flat-panel photobioreactors* (PBRs) are under development by Colt, ARUP, and SSC (Strategic Science Consult) for the Federal Ministry of Transport, Building and Urban Development, Germany. These cultivate microalgae as an energy resource, as demonstrated in the first application of an integrated system in a four-story residential building, BIQ House, in Hamburg, Germany (see Fig. 7.16). The BIQ House has 129 flat-panel glass bioreactors on the southwest and southeast facades, which facilitates photosynthesis. ARUP's Europe Research Leader, Jan Wurm, writes (Wurm, 2012): "This passive-energy house generates biomass and heat as renewable energy resources while also having a dynamic shading device, thermal insulation and noise abatement. . . . The microalgae circulate through the panels with water and nutrients, absorbing light and carbon and producing biomass. The part of the solar spectrum that isn't absorbed by the algae heats the water, and this solar thermal heat is removed so it can be used in the building or stored for when it's needed."

(*a*) (*b*) (*c*) (*d*)

Fig. 7.16 *Photobioreactors in the BIQ House: (a) southeast and southwest elevations of the world´s first SolarLeaf-Building in Hamburg, Germany, with 200 m² (2153 ft²) of active SolarLeaf area; (b) Panels track solar radiation around a vertical axis; (c) SolarLeaf louver with hidden horizontal support system; (d) AirLift-System bubbles rising in the SolarLeaf louvers. (© Colt International, Arup Deutschland, SSC GmbH; used with permission.)*

The PBRs are linked in a closed loop to the building's plant room where they are fed with carbon from combustion processes in the neighborhood. After harvesting, the algae are transformed into methane, and the heat generated is taken out of the system by heat exchangers. It is stored geothermally or fed back into the building using a heat pump, for heating and hot water supply. Some of the benefits include:

- Generation of biomass as a renewable energy resource in the urban context (the calculated net energy gain is approximately 30kWh per square meter [2.8 kWh/ft^2)] per year)
- Additional generation of solar thermal heat of around 30kWh per square meter (2.8 kWh/ft^2) per year
- Absorption of carbon directly at the source of domestic or industrial emissions agents

7.7 HEAT FLOW VIA AIR MOVEMENT

Outdoor air can enter a building by means of infiltration and/or ventilation. *Infiltration* is an unintended influx of outdoor air due to air leakage through the building skin. *Ventilation* is a deliberate, designed introduction of outdoor air. In either case, air at a different temperature and humidity interacts with the air inside a building. This interaction brings sensible and latent heat loads. Of the two means of air entry, infiltration is the more difficult to predict, since it is by definition unintended. Ventilation air quantities are intended and thus easily quantified. Although it is possible for infiltration and ventilation to occur simultaneously, usually it is reasonable to assume one of the following scenarios: only infiltration (which is typical of many smaller buildings with no mechanical ventilation) or only ventilation (which is typically required by code for larger buildings, and which usually pressurizes a building and blocks infiltration). Both infiltration and ventilation airflow rates are expressed in cubic feet per minute (cfm); the SI units are liters per second (L/s).

(a) Infiltration

The main problem with infiltration is estimating how much air will leak into a building once it is built. There are two primary means of calculating the infiltration airflow rate during design: the air-change method and the crack method.

The *air-change method* is very simple and quick but tends to overestimate. Air-change is a correlational method wherein observed performance of a set of existing buildings is matched (correlated) to key characteristics of a proposed building. The characteristics used are construction type and climate. Virtually no detailed information about a building or its spatial arrangement is required. Table F.3 lists estimated air changes per hour (ACH) as a function of these two characteristics. ACH is indicative of the "turnover" of air within a building or space. The greater the ACH, the greater the rate of outdoor airflow. A fairly tight building might permit 0.50 ACH or so, a recently-built leaky building 1.50 ACH. ACH can be converted to airflow rate as follows:

$$\frac{V = (\text{ACH}) \times (\text{volume, ft}^3)}{60\ \text{min/h}}$$

where V is airflow rate in cfm.

In SI units:

$$\frac{V = (\text{ACH}) \times (\text{volume, m}^3)}{3600\ \text{sec/h}}$$

where V is in m^3/s. Although both m^3/s and L/s are used as SI units of airflow rate, L/s is more commonly encountered in building design work. L/s = m^3/s × 1000.

The *crack method* requires more effort and assumes that data on window and door construction and wind velocities are known. It also assumes that all infiltration under design conditions is due to cracks around doors and windows. To estimate the airflow rate, calculate the length of cracks on the windward exposure(s) only, and multiply this by the respective assembly air leakage rate(s) as follows:

$$V = (\text{total lin. ft of window/door edge}) \times (\text{air leakage rate(s), cfm per lin. ft})$$

where V is in cfm.

In SI units:

$$V = (\text{total lin. m of window/door edge}) \times (\text{air leakage rate(s), L/s per lin. m})$$

where V is in L/s.

See Table E.15 for generic air leakage data or get NFRC or manufacturer's ratings for a specific fenestration product. If air leakage rates are unknown, Table F.4 shows how much leakage per unit length of crack should be assumed, for the windward exposure(s) only, to arrive at the total infiltration airflow rate. Multiply the total length of crack by the infiltration rate from part B of Table F.4.

It is possible to measure the actual infiltration performance of a constructed building using a fairly simple device called a *blower door*. Energy codes are increasingly requiring that building tightness be verified by a blower door test. As a result, local utility companies may be able to provide reasonably accurate values for air-change rates for buildings constructed using prevailing practices. Local experience data may provide better estimates of infiltration than the crack method.

(b) Ventilation

It is important to provide some minimum amount of fresh air to indoor environments as a means of IAQ control. Odors and a sense of staleness can be uncomfortable, and dangerous buildups of pollutants such as formaldehyde and radon can occur within buildings. These pollutants are most effectively removed via fresh airflow (although with a notable energy penalty). Tables F.1 and F.2 list recommended design outdoor airflow rates to produce acceptable IAQ. A more thorough discussion of IAQ is found in Chapter 5.

Many building codes require a minimum outdoor airflow rate based upon either building population or floor area. These requirements are generally based upon ASHRAE Standard 61.1 (nonresidential buildings) or ASHRAE Standard 62.2 (residential buildings). This minimum is often (but not always) provided by mechanically induced ventilation. Since ventilation is intentional, estimating such airflow rates is straightforward. With some simplification, when a building's required outdoor air (Table F.1) is based upon population:

$$V = (\text{cfm [or L/s] of outdoor air per person}) \times (\text{number of people})$$

When the required outdoor airflow rate is based upon floor area:

$$V = (\text{cfm [or L/s] of outdoor air per unit floor area}) \times (\text{total floor area})$$

7.8 CALCULATING ENVELOPE HEAT FLOWS

When the fundamentals of heat flow through a building envelope are understood, calculations to determine the magnitude of such flows can be undertaken. Three analyses of heat flow are usually of primary interest: (1) a design heat loss based upon "worst-hour" conditions, which is used to size heating systems, (2) a design heat gain (or cooling load) also based upon worst-hour conditions, which is used to size cooling systems, and (3) an annualized heat flow, based upon yearlong climate conditions, which is used to predict annual energy usage and costs and/or demonstrate compliance with energy standards. Hand calculations can provide reasonably accurate estimates of design heat loss and gain—even though the use of computer programs for these analyses is very common. Although a rough estimate of annual energy usage can be made using hand calculations, it is much more likely that a computer program will be used for this purpose. Many such programs are readily available, although they generally have a moderately steep learning curve and require detailed input information. Regardless of whether a manual or computerized calculation approach is taken, understanding the concepts and issues involved is critical to good design decisions.

(a) Design Heat Loss

Calculation of design heat loss is an attempt to estimate the reasonably-worst-likely hourly heat flow from a building to the surrounding environment. This value is used to size heating systems; the greater the design heat loss, the larger the required heating system capacity. The *design* heat loss is not the highest heat loss that can (or will) ever occur; rather, it is a statistically reasonable maximum heat loss based upon a chosen outdoor air temperature. By convention, design heat loss is assumed to occur at night (no sun), during the winter (coldest temperatures), with no occupants, lights, or equipment to offset heat lost through the envelope. These assumptions lead to an easy analysis based upon steady-state conditions.

To calculate the design (statistically-worst-hour) heat loss through a building's envelope, the following information is necessary:

1. The *rate* at which heat flows through each of the elements that make up the building envelope—i.e., the assembly U-factors (or equivalents)
2. The *area* (or perimeter) of each of these assemblies
3. The design *temperature difference* between inside and outside

With only the first two factors, a comparison of the thermal integrity of one building envelope versus another, in any location, can be made. These two factors are an outcome of the design process. The third factor, temperature difference, is a function primarily of climate, but also of comfort criteria. Design temperatures for various geographic locations (climates) are listed in Appendix B.

The design sensible heat loss through *all* types of aboveground elements of the building envelope can be calculated as follows:

$q = (U)(A)(\Delta t)$ for each element

I-P units: Btu/h = (Btu/h ft^2 °F) (ft^2) (°F)

SI units: W = (W/m^2 K) (m^2) (K)

where

q = hourly heat loss through a specific envelope component (by conduction, convection, and radiation) under design conditions

U = U-factor for a given envelope component

A = surface area of the envelope component

Δt = the design temperature difference between indoor and outdoor air (see Appendix B)

(If a *representative* heat loss is desired, use average temperatures such as from the latter part of Appendix C or local climatological data.)

In addition to the aboveground components, heat loss through at- and below-grade elements and via airflow must be estimated.

For slab-on-grade floors (see Example 7.3):

$q = (F_2)(P)(\Delta t)$

I-P units: Btu/h = (Btu/h ft °F) (ft) (°F)

SI units: W = (W/m K) (m) (K)

where

q = hourly sensible heat loss through the slab-on-grade floor under design conditions

F_2 = heat loss coefficient for the floor slab/insulation configuration

P = perimeter of the floor slab

Δt = design temperature difference between indoor and outdoor air

For below-grade basement walls and floors (see Example 7.4):

$q = (F)(A)(\Delta t)$ summed across various depths below grade of the wall/floor

I-P units: Btu/h = (Btu/h ft^2 °F) (ft^2) (°F)

SI units: W = (W/m^2 K) (m^2) (K)

where

q = hourly sensible heat loss through the basement wall/floor under design conditions

F = heat loss coefficient for the wall-floor/insulation configuration at a given depth below grade

A = area of the floor or wall at a given nominal depth below grade

Δt = design temperature difference between indoor air and surface of the ground

For airflow due to infiltration or ventilation, design sensible heat loss is calculated as follows:

$$q = (V)(1.1)(\Delta t)$$

where

q = sensible heat loss due to infiltration or ventilation (Btu/h)

V = outdoor airflow rate in cfm

Δt = temperature difference between outdoor and indoor air (°F)

1.1 = a constant derived from the density of air at 0.075 lb/ft^3 under typical building conditions, multiplied by the specific heat of air (the heat required to raise 1 lb of air 1°F, which is 0.24 Btu/lb °F) and by 60 min/h. The units of this frequently encountered, but quirky, constant are Btu min/ft^3 h °F.

In SI units, this becomes

$$q = (V)(1.2)(\Delta t)$$

where q is in watts, V is in liters per second, 1.2 is a constant (the density of air [1.20 kg/m^3] multiplied by the specific heat of air [1.0 kJ/kg K]), and Δt is in degrees K.

The total design sensible heat loss for a building is the sum of the component losses (aboveground elements, on-ground and belowground elements, and airflow). All the aboveground envelope elements could be lumped together (using an area-weighted U-factor) under the same equation (because assembly orientation, tilt, and transparency are of no consequence in the absence of sun). It is very useful, however, to identify the loss of each component (window, floor, roof, etc.) so that design improvements can focus upon those envelope components with the biggest contribution to overall heat loss. Design for energy efficiency in the building envelope essentially consists of trying to reduce the value of any variable that occurs on the right-hand side of these design heat loss equations. This is the design palette; no other design change will affect design heat loss:

- Reduce component U-factors (within the constraints of the budget and constructability).
- Reduce areas of components (within the constraints of the program and design intent).
- Reduce the design temperature difference (usually by lowering indoor air temperature, perhaps by microclimate improvement of outdoor conditions).
- Reduce airflow into the building (consistent with IAQ criteria).

In practice, design latent heat loss is often ignored. There are two reasons for this: (1) humidity (directly affected by latent loss) is often allowed to float during the winter, and (2) there is no single system or piece of equipment that will handle both sensible and latent heat loss. Even so, it is possible to estimate design latent heat loss for the various envelope elements. The calculation of latent heat loss through aboveground components involves an equation similar to that used for sensible heat loss:

$$q = (M)\,(A)\,(\Delta p)\,(C)$$

where

q = latent heat exchange due to vapor pressure difference, Btu/h (W)

M = permeance of the envelope element, lb/h ft^2 in. Hg (ng/s m^2 Pa)

A = surface area of the envelope component, ft^2 (m^2)

Δp = difference in vapor pressure between outdoor and indoor air, in. Hg (Pa)

C = an approximate value of energy content (enthalpy) under typical interior conditions, 1076 Btu/lb (2500 kJ/kg)

Because it is common to install a reasonably effective (very-low-permeance) vapor retarder in cold climate constructions, to minimize condensation problems, latent envelope heat loss is often assumed to be negligible. Because the on-grade and belowground portions of a building are commonly waterproofed with very-low-permeability materials, these components are typically assumed to be impermeable and to support no latent heat loss. Substantial latent loss can occur, however, as a result of airflow.

The design latent heat loss due to the flow of outdoor air into a space is calculated as follows:

$$q = (V)\,(4840)\,(\Delta W)$$

where

q = latent heat exchange due to ventilation (Btu/h)

V = outdoor airflow rate in cfm

ΔW = difference in humidity ratio between outdoor and indoor air (lb of moisture/lb of dry air)

4840 = a constant derived from the density of air (0.075 lb/ft^3) multiplied by the heat content of water vapor (1076 Btu/lb) and by 60 min/h. The density and heat content values noted are for conditions typical of interior environments.

In SI units, this becomes

$$q = (V)\,(3010)\,(\Delta W)$$

where q is in watts, V is in liters per second, W is in kJ/kg, and 3010 is the density of air (1.20 kg/m^3) multiplied by the heat content of water vapor (2500 kJ/kg for typical indoor conditions).

(b) Design Heat Gain

The calculation of design heat gain (more correctly called *cooling load*) is far more complex than the calculation of design heat loss. The simplifying assumptions made for winter conditions (nighttime with no sun and ignoring occupancy-related heat sources) are untenable for a summer situation. There is sun during the "worst" summer hour, and the highest temperatures are usually in the afternoon, when a nonresidential building would be in full work mode with occupants, lights, and equipment generating heat. In a nutshell, design cooling load calculations must deal with many more variables—including the compounding effects of solar radiation, which create the need for dynamic heat flow analysis. Things get very complicated.

There are hand-calculation methods for estimating design cooling load, and computer programs to do the same. It is important, however, to establish the conditions under which such calculations are conducted. In addition to the design variables that affect design heat loss (envelope assembly U-factor, surface area, temperature difference, and airflow rate), the following variables will affect design cooling load:

- The orientation of an assembly (north, south, etc.)
- The tilt of an assembly (vertical, horizontal, inclined)
- The surface reflectance of an assembly
- The thermal capacity of an assembly
- The solar heat gain coefficient of a transparent/translucent assembly
- Shading for any envelope component
- Heat gain (sensible and latent) from occupants
- Heat gain from lighting
- Heat gain (sensible and latent) from equipment

Design decisions influence all of these variables and therefore the resulting design cooling load. This list of variables is again the palette from which energy-efficiency decisions may be selected. It is critical that this palette be fully appreciated early in the design process and not be delegated to a mechanical engineering consultant who may enter the design process too late to provide effective advice.

How does design *heat gain* differ from design *cooling load*? In the past, calculations for summer loads simply totaled all the heat flows at a given hour that entered or originated inside of a building envelope. This total instantaneous heat flow is known as *heat gain*. It turns out, however, that some of this instantaneous gain does not immediately affect indoor air temperature—this is specifically true of radiation heat flows that are absorbed and stored by the internal mass of a building. Those heat gains that affect air temperature at the hour of interest are collectively called the *cooling load*. It is only this distinct subset of heat gains that must be handled (at the time) by a cooling system. Conceptually, cooling load is equal to instantaneous heat gain minus any part of that heat gain that is stored within the building, plus any previously stored gains that are now affecting air temperature (through release from storage). The distinction can be substantial, providing first cost savings in equipment capacity and life-cycle savings through improved operating efficiency.

Solar radiation plays an important role in building envelope heat gain, and not just via transparent/translucent components. The impact of solar radiation on opaque construction assemblies can be substantial. The concept of sol-air temperature helps to illustrate this impact. *Sol-air temperature* is the apparent outdoor air temperature that would produce the same heat flow experienced under the combined effects of temperature difference (based upon actual outdoor air temperature) and radiation. Essentially, sol-air temperature lumps the heat flow caused by radiation absorbed and retained by a surface with the heat flow caused by the air-to-air temperature difference. This is a convenient concept, as it produces a delta-*t* value that can be plugged into the conventional heat gain equation. The simplified sol-air temperature formula (in I-P units) is:

$$t_e = t_o + \frac{\alpha \times I}{h_o} - 7^{\circ}\mathrm{F}$$

where

t_e = sol-air temperature

t_o = outdoor (ambient) dry-bulb temperature

α = absorptance of surface for solar radiation (for light-colored surfaces, usually assumed as 0.45; for dark-colored surfaces, usually assumed as 0.90; detailed values are listed in Table 12.11)

I = total solar radiation incident on the surface, Btu/h ft^2 (see Appendix C for solar heat gain factors, which are approximately equivalent to I for horizontal surfaces)

h_o = coefficient of heat transfer by long-wave radiation and convection at the surface (usually assumed as 3.0 Btu/h ft^2 °F)

The simplified sol-air temperature formula in SI units is:

$$t_e = t_o + \frac{\alpha I}{h_o} - 3.9^{\circ}\mathrm{C}$$

where the differences from I-P units are as follows:

I = total solar radiation incident on the surface, W/m^2

h_o = usually assumed as 17.0 W/m^2 K

EXAMPLE 7.6 What is the sol-air temperature for a horizontal white roof, compared to a dark roof, on a clear July 21 at noon, at 40°N latitude? Assume outdoor air temperature of 90°F (32°C).

SOLUTION

From Table C.3 of Appendix C, on July 21 at noon at 40°N latitude, the solar heat gain factor on a horizontal surface = 262 Btu/h ft^2 (827 W/m^2).

$$\text{Sol-air temperature: } t_e = t_o + \frac{\alpha I}{h_o} - 7°\text{F}$$

For a white roof:

$$t_e = 90°\text{F} + \frac{0.45 \times 262\,\text{Btu/h ft}^2}{3.0\,\text{Btu/h ft}^2\,°\text{F}} - 7°\text{F}$$

$$= 90 + 39.3 - 7 = 122.3°\text{F}$$

For a dark roof:

$$t_e = 90°\text{F} + \frac{0.90 \times 262\ \text{Btu/h ft}^2}{3.0\ \text{Btu/h ft}^2\,°\text{F}} - 7°\text{F}$$

$$= 90 + 78.6 - 7 = 161.6°\text{F}$$

In SI units: $t_e = t_o + \alpha I \backslash h_o - 3.9°\text{C}$

$$t_e = 32°\text{C} + \underline{0.45 \times 827\ \text{W/m}^2/17\ \text{W/m}^2\ \text{K}} - 3.9°\text{C}$$
$$= 50.0°\text{C}$$

$$t_e = 32°\text{C} + \underline{0.90 \times 827\ \text{W/m}^2/17\ \text{W/m}^2\ \text{K}} - 3.9°\text{C}$$
$$= 71.9°\text{C}$$

Solar radiation has a marked impact upon surface temperature (and resulting heat flow). Elevated temperatures in full sun will drive considerably more heat through both roofs compared to shaded conditions. The white roof has a Δt about 1.4 times greater in full sun than in shade. The dark roof has a Δt about 1.3 greater than the white roof under the stated conditions. ■

7.9 ENVELOPE THERMAL DESIGN STANDARDS

The building design team will find that there are code requirements that establish minimum thermal envelope performance requirements for virtually all jurisdictions in North America and for virtually all building types. In the United States, code adoption is a local matter, and the specific energy code to be followed depends upon the jurisdiction. Even so, the energy code most likely to be encountered for nonresidential buildings is ASHRAE Standard 90.1. In California, Title 24 is the statewide counterpart of Standard 90.1. Residential buildings are likely to fall under the requirements of the *International Energy Conservation Code* or its predecessor *Model Energy Code*—both of which are really standards until adopted as law. ASHRAE also publishes a residential energy standard, Standard 90.2. Although energy codes provide efficiency requirements for more than just the envelope (usually also dealing with HVAC equipment efficiency, hot water heating, and lighting), this discussion focuses upon envelope requirements.

It is typical for energy codes to provide two paths to compliance: (1) a prescriptive path, which provides precise statements of minimally acceptable component characteristics (for example, a minimum R for wall insulation or a maximum U for a window), and (2) a performance path, which sets a minimum level of overall energy performance that may be met using a wide range of solutions. Code compliance via the prescriptive path is usually straightforward and requires little analysis or creativity. Following the performance path may require detailed analysis (usually by way of a computer program) and opens the door to innovation and creativity.

Energy codes need to be placed in context. They establish a set of minimum requirements. Just barely meeting an energy code simply means that a building envelope is not illegal. In today's design environment, doing better—perhaps much better—than the minimum required by code is becoming a common design approach. The U.S. Green Building Council (USGBC) LEED rating system, for example, requires compliance with ASHRAE 90.1 performance targets as a prerequisite for green building status. To actually gain any points toward a green building rating, a design must exceed these minimum requirements (by variable percentages, depending upon the points sought). ASHRAE has released numerous volumes in its *Advanced Energy Design Guide* series (distinct from the 90.1 energy standard) to assist in the design of buildings that will perform 30% (or 50%) better than a 90.1-compliant building. No matter the target, the building envelope will always play an important role in building energy performance.

Appendix H provides excerpts from three influential high-performance building design standards and guidelines. The excerpts include:

- A sample of the prescriptive envelope requirements from ASHRAE Standard 90.1 (nonresidential buildings)
- A sample of recommendations from the 50% *Advanced Energy Design Guide for Small to Medium Office Buildings*
- The scorecard (criteria set) for LEED certification of new buildings (version 4)

The ASHRAE standards/guidelines and LEED criteria are continuously being updated. The intent of these excerpts is not to provide the most current information, but rather to show the general format by which such design requirements are conveyed.

EXAMPLE 7.7 A two-story medical office building is being designed for Indianapolis, Indiana. What are the maximum permissible U-factors (and other envelope characteristics) for such a building in this location?

SOLUTION

Refer to Appendix B for climate data and to Appendix H (Table H.1) for sample provisions of ASHRAE Standard 90.1-2013.

- Climate: Indianapolis, Indiana: HDD65: 5615 (SI: HDD18 = 3119); CDD50: 3453 (SI: CDD10 = 1918). Indianapolis is in Climate Zone 5. (HDD and CDD values, as well as Climate Zone, can be obtained from Standard 90.1 or another data resource.)

These benchmark climate indicators (heating and cooling degree days: HDD and CDD, respectively) can be used to establish which set of prescriptive requirements in Standard 90.1 apply to a building in Indianapolis (or the map in Standard 90.1 can be used for the same purpose). Within the applicable climate zone data set (in this case, only Zone 5 information is shown in Table H.1), note that one of the labeled columns of design values applies to a nonresidential (for this example, an office) building, while the other columns apply to other building contexts.

- Roof: maximum U-factor: 0.027 (SI: 0.153), assuming a roof/attic construction as typical of this type of building
- Frame walls: If wood framed, the maximum U-factor is 0.064 (SI: 0.36); if steel framed, the maximum U-factor is also 0.064 (SI: 0.36).

Looking at the Above Grade Wall data shows that the U-factor requirements vary with the type of construction (ranging from 0.064 to 0.090). This "flexibility" in performance requirements reflects the fact that Standard 90.1 is a consensus document attempting to satisfy many constituencies, and that it is not based on scientific absolutes or idealized efficiencies.

- Floor (assuming wood-framed, over a crawl space): maximum U-factor: 0.033 (SI: 0.187)
- Opaque doors: maximum U-factor: 0.70 (SI: 4.0), assuming swinging doors

Doors are a substantial weak link in the thermal envelope resistance but are usually a small percentage of the overall wall area.

- Windows: If operable windows constitute 25% of the wall area (or even up to 40%), their maximum U-factor is 0.35 (SI: 1.98), and the maximum SHGC is 0.40.

Compare the minimum acceptable ("code-minimum") envelope properties outlined here with the recommended properties given in Table H.2—which contains excerpts from the 50% *Advanced Energy Design Guide* for offices. ■

7.10 CASE STUDY—HEAT FLOW AND ENVELOPE DESIGN

This section presents three case study projects, including a multifamily housing project, a school, and a commercial office retrofit. The projects demonstrate both the successful implementation of many Passive House strategies and their scalability and versatility across climate zones and beyond newly constructed, single-family detached dwellings.

Background. The Passive House standard is commonly regarded as one of the most stringent energy standards in the world. Applicable to both residential and commercial building types, the standard seeks to improve occupant comfort while simultaneously minimizing building energy use. Certified buildings regularly achieve a 90% baseline energy reduction and can typically achieve net-zero source energy with the integration of a relatively small supplementary renewable energy system. Certified buildings are superinsulated and very airtight, such that they can rely almost exclusively on internal and solar gains for heating. Per the standard, indoor air quality must be well maintained, typically through the use of a heat recovery ventilator (HRV) or energy recovery ventilator (ERV), which supplies a constant volume of fresh outdoor air.

It is important to emphasize the suitability of the Passive House approach beyond single-family, residential construction. While most commonly applied to single-family dwellings, the principles can be successfully implemented across a range of project types and building scales. To better reflect this versatility, "Passive House" may undergo a name change (time will tell). For the sake of clarity, projects are referred to as "Passive House buildings," to emphasize that the standard can be broadly applied.

Design Intent. Among the most notable characteristics of the Passive House standard is its simultaneous simplicity and rigor. The standard has four primary requirements:

- Heating energy use must be less than 4.75 kBtu/ft^2 per year (15 kWh/m^2 per year).
- The peak heat load must be less than 1 W/ft^2 per hour (10 W/m^2).
- Air leakage must be less than 0.6 air changes per hour (ACH), measured at 50 pascals.
- Total primary (source) energy use must be less than 38 kBtu/ft^2 per year (120 kWh/m^2 per year).

In addition to these energy criteria, designers must meet several equally challenging thermal comfort requirements. These aim to maintain a constant and comfortable ambient temperature throughout the building and to reduce radiant asymmetry by maintaining a minimum difference of 7.6F° (4.2C°) between all surface temperatures and the ambient air temperature.

Designers must also specify glazing elements and mechanical systems that meet minimum Passive House performance criteria, and the project team must verify the building's airtightness on-site several times throughout the construction process—typically immediately after the envelope is finished, again before the interior walls are put in, and finally upon completion of the building.

The Center for Energy Efficient Design (CEED)

Project Basics

- Location: Rocky Mount, Virginia, USA
- Latitude: 36.99 N; longitude: 79.89 W; elevation: 1232 ft (376 m)
- Heating degree days: 4228 base 65°F (2383 base 18.5°C); cooling degree days: 4158 base 50°F (2309 base 10°C); annual precipitation: 41 in. (1042 mm)
- Building type: K–12 educational facility
- Floor area: 3053 ft^2 (284 m^2)
- Completed: 2011
- Design team: Structures Design/Build (architects, contractor, Certified Passive House Consultant)

Context. As the first Passive House–certified public school in the U.S., the Center for Energy Efficient Design [CEED] was built to teach. Incorporated into a building-specific curriculum, CEED serves as a demonstration of environmental science and design principles for middle- and high-school students. Additionally, the building is open to interested designers, builders, and homeowners as a showcase of successfully integrated energy-efficient design strategies. Continuous, real-time building monitoring allows students to understand relationships between design, occupant behavior, and immediate environmental impact.

Key Design Features

Massing. A simple form both minimizes building footprint and reduces building surface area, thereby reducing heat transfer through the building envelope. In general, Passive House–certified buildings rely on low-surface-area forms to minimize envelope heat loss and infiltration. Any bump-outs and façade articulations are carefully considered and optimized for solar control. Depending on climate, building massing is optimized for passive solar heating.

Employing classic passive solar design principles, CEED's compact shape, strategic siting, and heavily glazed south façade capitalize on the heating benefits of the winter sun. Shown in Fig. 7.17, a permanent trellis system shades these south-facing windows from summer solar heat gain.

Fig. 7.17 CEED's expanse of south-facing glazing takes advantage of winter solar heat gain. This and other passive strategies enabled this public school to reach net-zero-source energy through the addition of a small renewable energy system. (© Structures Design/Build LLC; used with permission.)

Mechanical Systems. Mechanical systems in Passive House–certified buildings are characterized by their simplicity and efficiency. A small heat recovery ventilator (HRV) or energy recovery ventilator (ERV) is the most commonly used system to provide thermal comfort and a constant supply of fresh outdoor air. In residential buildings, air is typically supplied to living spaces and exhausted from kitchen and bathroom spaces; the ERV or HRV is centrally placed to minimize duct runs.

The mechanical systems at CEED address an interesting challenge common to nonresidential buildings: how to efficiently provide adequate air supply to variable-occupancy spaces. Challenged by limited U.S. equipment availability and Virginia's mixed humid climate, the design team implemented a two-stage variable speed ERV system. ERV intake air is first heated, cooled, or dehumidified using a water-to-air heat exchanger; this heat exchanger can circulate either solar hot water or brine from a passive ground loop. Stage two, a ground-source heat pump, is used for periods of higher occupancy, when additional cooling is required.

Validation. CEED is continuously monitored. Sensors measure wind speed, indoor and outdoor temperatures, relative humidity, solar panel and wind turbine performance, ground-source heat pump performance, CO_2 levels, and rainwater harvesting performance. The data, which are shown in Fig. 7.18, are shared publicly as a component of the school's mission in environmental education.

A thermal comfort survey, which was administered one year after occupancy, demonstrated overwhelming satisfaction with the building's indoor environmental quality: 0% of respondents reported dissatisfaction in all assessed categories, which included dry-bulb and radiant temperatures, humidity, air speed, and air and lighting quality.

Glasswood

Project Basics

- Location: Portland, Oregon, USA
- Latitude: 45.52 N; longitude: 122.78 W; elevation: 39 ft (12 m)

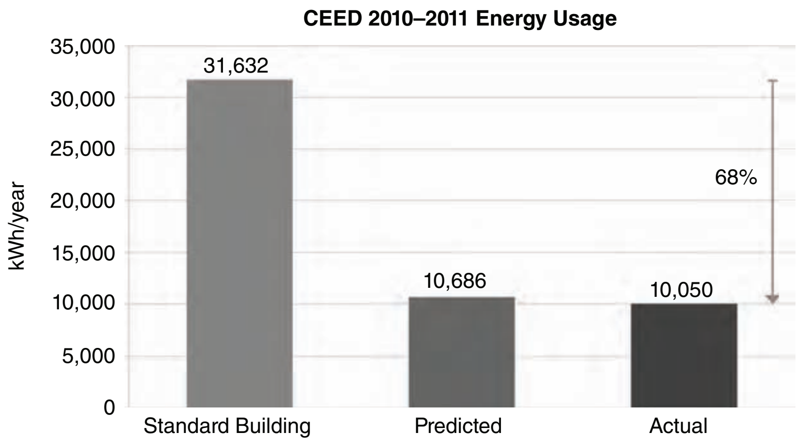


Fig. 7.18 *Post-occupancy energy monitoring data measured at the Center for Energy Efficient Design in Rocky Mount, VA. (© Structures Design/Build; used with permission.)*

- Heating degree days: 4428 base 65°F (2509 base 18.5°C); cooling degree days: 2790 base 50°F (1548 base 10°C); annual precipitation: 36 in. (914 mm)
- Building type: Commercial
- Floor area: 1397 ft^2 (130 m^2)
- Completed: 2012
- Design team: Scott Edwards Architecture (architects); Hammer & Hand (contractor, Certified Passive House Consultant)

Context. Glasswood, the first Passive House commercial retrofit project in the United States, brings energy performance to a 1916 building on the east side of Portland. The project's Passive House potential was clear from the start, as the framing was essentially the only usable component of the existing building. Through reconstruction of the building's envelope, the design team sought to preserve the historic aesthetic of the building while providing a modern, high-performance update to the materials and construction. The two-story building houses offices on the upper floor and a restaurant on the first. While the thermal comfort and energy efficiency of both floors of the building were drastically upgraded, only the top floor pursued Passive House certification.

(*a*) (*b*)

Fig. 7.19 *A comparison of before (a) and after (b). Glasswood's Passive House retrofit shows the preservation of the façade design and historic aesthetic. (© Hammer & Hand; used with permission.)*

Key Design Features

Superinsulation and Hygrothermal Performance. Like the cutting-edge 1970s houses from which the Passive House standard was derived, certified buildings feature highly insulated envelopes, with typical wall assembly R-values ranging from 35 to 55 Btu/hr ft^2 °F (7–10 W/m^2 K) and roof assembly R-values ranging from 60 to 90 Btu/hr ft^2 °F (10–17 W/m^2 K). Unlike their 1970s counterparts, however, modern enclosure assemblies are carefully analyzed for their hygrothermal performance to assess the degree of vapor diffusion through the assembly.

Shown under construction in Fig. 7.20, Glasswood's existing 2×4 (50 × 100 mm) wood stud wall was upgraded to a 12-inch (305 mm) double-stud framing system. The second stud wall was built inboard of the existing framing and serves as a service cavity. A 2-inch (50 mm) layer of EPS foam outboard of the existing framing supplements the thermal resistance achieved by the cellulose in the two wall cavities.

As the complexity of the assembly increases, so must the rigor of its hygrothermal analysis. Components must be thoughtfully organized to reduce the potential for vapor condensation and accumulation, which is a precursor to mold growth. In Glasswood, extensive hygrothermal modeling was used to verify the "vapor-open" nature of the assembly: While the assembly is both airtight and highly thermally resistive, moisture is allowed to dry to both sides.

Air Sealing. One of many energy-saving measures required of Passive House–certified buildings is a continuous air barrier. Great care (and much tape) is required to ensure that the "airtight layer," which includes floor, walls, and ceiling, remains free of both intentional and unintentional holes.

Shown in Fig. 7.21, Glasswood's airtight layer is formed by 0.5 in. (12 mm) OSB, which is carefully taped at its seams. This layer is placed between the two 2×4 (50 × 100 mm) stud walls. This strategic placement protects the airtight layer from weather and from occupant wear, and it minimizes necessary service punctures to the airtight layer, as the service cavity is placed in the innermost stud wall.

Energy monitoring in Glasswood reveals the importance of controlling plug loads. A circuit-by-circuit energy monitor was installed; the real-time feedback allowed occupants to keep wasteful loads in check and remain below their targeted annual energy use.

Thermal comfort studies were equally revealing. The original design did not include external sunshades, which resulted in excessive solar heat gain during the shoulder seasons. Rather than relying on the mechanical system to maintain comfortable temperatures, as the original design prescribed, the occupants installed external shades on the south-facing façade. The experience proved educational for the office occupants, who are building science professionals themselves; one occupant reports, "I think exterior shades are one of the most critical components of HVAC design."

__Fig. 7.20__ A construction phase photo of Glasswood reveals the outermost 2×4 (50 × 100 mm), cellulose-filled stud wall before construction of the airtight layer. (© Hammer & Hand; used with permission.)

__Fig. 7.21__ Glasswood's airtight layer is made of 0.5-in. (12 mm) tiled OSB sheets, whose seams are carefully sealed with tape. The airtight layer was placed between the two stud walls for protection. (© Hammer & Hand; used with permission.)

After this very simple modification to the initial façade design, occupants report very high persistence of thermal comfort with a low energy use.

Stellar Apartments

Project Basics

- Location: Eugene, Oregon, USA
- Latitude: 44.12 N; longitude: 123.22 W; elevation: 357 ft (109 m)
- Heating degree days: 4913 base 65°F (2781 base 18.5°C); cooling degree days: 2519 base 50°F (1402 base 10°C); annual precipitation: 46 in. (1168 mm)
- Building type: Multifamily housing
- Floor area for building type (6 units/building): 5626 ft^2 (523 m^2); 5069 ft^2 (471 m^2) conditioned floor area for Passive House building type
- Completed: August 2013
- Client: St. Vincent de Paul Society of Lane County
- Design team: Bergsund Delaney Architecture (architects), Meili Construction (contractor), SOLARC (energy consulting), Ecobuilding Collaborative of Oregon (energy consulting)

Context. The Stellar Apartments, a 54-unit affordable housing complex just west of downtown Eugene, Oregon, seeks to provide occupant thermal comfort and energy performance without the commonly associated rent premiums. Each of the complex's 12 buildings complies with the Earth Advantage Certification, but one building reaches further, targeting Passive House certification. Though the ambitious energy targets required by each of the standards raised the project's first cost, the choice to proceed was fairly easy for the client. Utility costs are rising faster than rental costs for consumers; thus, enhanced energy performance

Fig. 7.22 The front elevation of the Stellar Apartments, a portion of an affordable housing project that was built to the Passive House standard, features strategically placed and responsibly shaded windows. (© Bergsund Delaney Architecture and Planning; used with permission.)

reduces the monthly financial burden for low-income tenants.

Key Design Features

High-Performance Components. Envelope components in a Passive House building must meet minimum performance thresholds; these are informed both by energy considerations and by thermal comfort criteria, which limit the allowable U-values of glazed components.

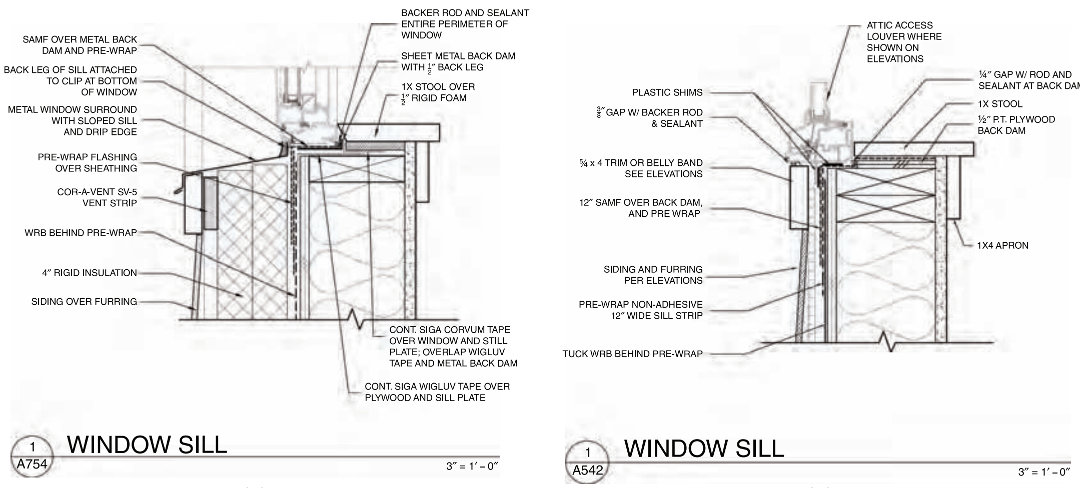
The Stellar Apartments Passive House building envelope components are no exception. The U-values of the European tilt-turn windows are considerably lower than those of the glazing systems specified in the Earth Advantage buildings in the complex (and at a price). The higher performance reduces conductive/convective heat loss and radiant temperature asymmetry caused by cold glazing surfaces. While high-quality components typically have higher first costs, the payback periods are often relatively short. Furthermore, increased adoption of more rigorous building practices will only reduce prices and increase domestic availability of higher-performance components.

Thermal-Bridge-Free Detailing. More so than perhaps any other standard, Passive House design and construction require meticulous attention to detail. Careful detailing and construction of joints and attachment points minimize both thermal bridging and air infiltration. Figures 7.23 and 7.24 show window details from different buildings in the Stellar Apartment complex. The comparison illustrates the rigor of the Passive House approach relative to a somewhat-better-than-business-as-usual construction. The thermal breaks and layers of tape found in the Passive House detail are common, relatively inexpensive detailing modifications that improve thermal resistance and airtightness of connection points, as in the example shown.

Validation. Energy performance information was unavailable at the time of publication, as construction was just reaching completion. The local utility has provided $20,000 to St. Vincent de Paul to support post-occupancy energy monitoring of two of the buildings in the Stellar complex (one Passive House building and one Earth Advantage building). The buildings will be monitored for a minimum of one year.

At the time of publication, the project team was performing the requisite post-construction blower door test. Results showed an airtightness of 0.50 ACH_{50}, below the 0.6 ACH_{50} required of the Passive House standard. Tests of the Earth Advantage comparison building showed substantially higher air leakage.

Each of these projects relied on extensive energy modeling to meet certification criteria. Feedback from the Passive House Planning



(*a*) (*b*)

Fig. 7.23 *A comparison of the windowsill details of the Passive House building (a) and the Earth Advantage building (b) at the Stellar Apartments. (© Bergsund Delaney Architecture and Planning; used with permission.)*

(a) (b)

Fig. 7.24 *A comparison of window assemblies of the Stellar Apartments' Passive House–certified building (a) to those of a noncertified building in the same complex (b) reveals the significantly thicker walls and advanced window assemblies typical of Passive Houses. (© Alison Kwok, all rights reserved.)*

Package [PHPP], an Excel-based energy modeler, is often used as a design driver in Passive House design development, allowing project teams to understand the energy (and certification) implications of various design iterations. PHPP's accuracy has been verified by corroborating field measurements across a range of climate zones and building types.

Many Passive House design teams will supplement the PHPP with WUFI, a dynamic hygrothermal-modeling tool, and with THERM, which analyzes two-dimensional heat transfer through building details. In 2013, the developers of WUFI created WUFI Passive, an integrated energy modeler designed specifically for the Passive House standard, which combines the capabilities of the static PHPP model with those of the dynamic WUFI model to create a streamlined and more convenient Passive House modeling tool.

FOR FURTHER INFORMATION

Stellar Apartments [Bergsund/Delaney Architecture]: http://www.bdarch.net

Glasswood [Hammer and Hand]: http://hammerandhand.com/glasswood-passive-house-retrofit

Center for Energy Efficient Design [Structures Design/Build]: http://ceed.frco.k12.va.us/

Passive House Alliance U.S.: http://www.phaus.org

Passive House Institute U.S.: www.passivehouse.us

Passive House Institute: http://www.passivehouse.com

Sereni, B. and G. Irwin. 2012. "The Passive House Retrofit," *Solar Today*, March/April 2012. http://www.solartoday-digital.org/solartoday/20120304?pg=3#pg18/

Gordon, J. 2009. "The Aggressive Standard of a Passive House," *Dwell*, November 2009. http://www.dwell.com/green/article/passive-acceptance/

References and Resources

AECInfo (with links to insulation manufacturers' Web sites). http://www.aecinfo.com/

Several publications of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA:

30% Advanced Energy Design Guide series. 2004–2012.

50% Advanced Energy Design Guide series. 2011–2012.

ASHRAE Handbook—Fundamentals. 2013.

ASHRAE Standard 62.1-2013, *Ventilation for Acceptable Indoor Air Quality*.

ASHRAE Standard 62.2-2013, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*.

ANSI/ASHRAE/IESNA Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

ANSI/ASHRAE Standard 90.2-2007, *Energy-Efficient Design of Low-Rise Residential Buildings*.

ANSI/ASHRAE Standard 189.1-2011, *Standard for the Design of High-Performance, Green Buildings Except Low-Rise Residential Buildings*.

BuildingGreen.com. 2011. "Insulation: The BuildingGreen Guide to Insulation Products and Practices." *Environmental Building News*. http://buildinggreen.com/landing/insulation/

Bynum, R. T., Jr. 2001. *Insulation Handbook.* McGraw-Hill. New York, NY.

Carmody, J., S. Selkowitz, and L. Heschong. 2007. *Residential Windows: A Guide to New Technologies and Energy Performance*, 3rd ed. W. W. Norton and Company. New York, NY.

Carmody, J., S. Selkowitz, E. Lee, D. Arasteh, and T. Willmert. 2003. *Window Systems for High-Performance Buildings*. W. W. Norton & Company. New York, NY.

CRRC. 2013. Cool Roof Rating Council. http://www.coolroofs.org/

Efficient Windows Collaborative. http://www.efficientwindows.org/

ICC. 2012. *International Energy Conservation Code.* International Code Council. Falls Church, VA.

ICC. 2012. *International Green Construction Code*. International Code Council. Falls Church, VA.

Lawrence Berkeley National Laboratory, Building Technology and Urban Systems. http://eetd.lbl.gov/about-us/organization/building-technology-and-urban-systems

Lstiburek, J. and J. Carmody. 1994. *Moisture Control Handbook: Principles and Practices for Residential and Small Commercial Buildings.* John Wiley & Sons. Hoboken, NJ.

Melody, I. 1987. *Radiant Barriers: A Question and Answer Primer*. Florida Solar Energy Center (FSEC-EN-15). Cocoa, FL. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-EN-15-87.pdf

National Fenestration Rating Council (NFRC). *Certified Products Directory.* NFRC Incorporated. Silver Spring, MD. http://www.nfrc.org/

NIBS. 2012. NIBS Guideline 3-2012, *Building Enclosure Commissioning Process*. National Institute of Building Sciences. Washington, DC. http://www.wbdg.org/ccb/NIBS/nibs_gl3.pdf

Norberg-Schulz, C. 1965. *Intentions in Architecture.* MIT Press. Cambridge, MA.

NREL. 2013. Research Support Facility, National Renewable Energy Laboratory. http://www.nrel.gov/sustainable_nrel/rsf.html/

Oikos: Green Building Library (including building envelope components). http://www.oikos.com/library/index.html

Sweet's System Online (links to insulation product manufacturers' WWW sites). http://products.construction.com/

Wilkinson, G. 1999. "Beyond *R*-Value—Insulating for the Environment." *Environmental Design and Construction,* January–February 1999.

Wurm, Jan. 2012. "Bioreactive Façade with Photobioreactors for Cultivating Microalgae as an Energy Resource." *ARUP Thoughts*, 15 May. http://thoughts.arup.com/post/details/199/bioreactive-facades

PART III

PASSIVE ENVIRONMENTAL SYSTEMS

The passive environmental systems constituting Part III focus on a designer's understanding of energy flows, form, comfort, and function derived from resources and energy that are essentially free. Chapter 8, "Daylighting," Chapter 9, "Passive Heating," and Chapter 10, "Passive Cooling," offer the designer guidance for building form and the verification of schematic design proposals utilizing daylight, solar energy, wind, water, soil temperatures, and the night sky as resources. Simple guidelines and detailed calculations, along with related codes, standards, and recommended practices, are presented with sample exercises and solutions. The final chapter in this part, Chapter 11, "Integrating Passive Systems," presents a fully realized project and supporting calculations for targeting passive design goals.

With building operations accounting for about 40% of global carbon emissions, we argue that the use of passive strategies to produce low-energy-use buildings is the road to a sustainable future.

CHAPTER 8

Daylighting

DESIGNING WITH DAYLIGHT IS BOTH AN ART AND A science. The designer, in concert with the appropriate combination of building geometries, materials, and light produced by site conditions, can produce health, well-being, and visual delight (Fig. 8.1), while also achieving an intended ambience and reducing dependency on electrical energy use. Although studies have demonstrated that daylighting improves indoor environmental quality for occupants, daylighting design is often mistakenly understood to mean that an abundance of light should fill a space.

(*a*)

(*b*)

Fig. 8.1 *(a) Visually appealing daylighting elements at Chiswick Park Office Complex, London, UK (Richard Rogers Partnership, 2002). (b) Hong Kong International Airport, Hong Kong, China (Norman Foster, 1998). (© Alison Kwok; all rights reserved.)*

Successful design involves a careful balance and control of heat gain and loss. A variety of strategies are available to control and enhance daylight through shading devices, lightshelves, glazing, atria, courtyards, and material finishes (both interior and exterior).

8.1 THE DAYLIGHTING OPPORTUNITY

(a) Importance of Daylighting Design

Historically, the architectural form of buildings, placement of windows, and location of rooms were guided by the availability of daylight as the primary source of illumination. Daylight was the only source of abundant light for buildings, provided through deep, tall windows and thick walls, and perhaps replaced (although inadequately) in the evening by the flicker of a candle flame or an oil lamp. Electrical lighting began around 1870 with the development of commercially usable arc lamps, and was given greater impetus nine years later by Edison's first practical incandescent lamp. Subsequently, building form changed dramatically with the development of fluorescent lighting technologies, allowing interiors to be uniformly lit by electric lighting systems and to function at cooler temperatures (as opposed to the higher temperatures produced by heat-intensive incandescent lamps). With such advances, buildings such as offices, shopping centers, and factories could now operate during evening hours.

Designing with daylight can improve energy efficiency by minimizing the use of electricity for lighting as well as reducing associated heating and cooling loads. Daylighting is a critical design factor to those concerned about global warming, carbon emissions, and sustainable design—in addition to visual comfort.

Research has found daylight to be an important factor influencing human behavior, health, and productivity. Windows admitting daylight provide occupants with a view and a temporal connection with the outdoors. Daylight renders the environment in a vivid range of experiences and delight. It is important for basic visual requirements to view tasks and to perceive space. How daylight is delivered is in the hands of the designer at the beginning stages of design. The option of ignoring daylight—in a world characterized by high energy costs and rapidly diminishing natural resources—is no longer viable. This chapter describes daylight strategies that can be used to increase occupant satisfaction, control glare, provide appropriate vertical and horizontal illumination, and address the potential for energy savings to enable the designer to create a proper visual environment.

(b) Planning for Daylight throughout Design

Designing buildings for daylighting is a complex systems integration process. Daylighting design begins with situating a building on its site and continues through each phase of design; making the best use of daylight continues throughout a building's occupancy. While overall design goals remain generally fixed throughout each design phase, there are key concerns associated with each of the phases. For example, in the conceptual design phase, building form, orientation, layout, and major apertures might be primary elements. Further into design development, there would be specification of materials and interior finishes, as well as zoning for integration with electric lighting and other services; control systems would be coordinated with occupancy schedules, and commissioning test procedures set in place. During occupancy, fine-tuning and maintenance of the system would occur, and a post-occupancy evaluation would be conducted, in order to determine satisfaction, visual comfort, and lighting system performance.

(c) Energy Savings with Daylighting

To obtain lighting energy savings in a building, six "essential" ingredients for daylighting design are recommended by the Illuminating Engineering Society of North America (IESNA) in RP-5-99, *Recommended Practice of Daylighting*:

1. Plan interior space for access to daylight.
2. Minimize sunlight in the vicinity of critical visual tasks.
3. Design spaces to minimize glare.
4. Zone electric lighting for daylight-responsive control.
5. Provide for daylight-responsive control of electric lighting.
6. Provide for commissioning and maintenance of any automatic controls.

Energy savings from reduced electric lighting will be compromised if any of these factors are overlooked. If any one of the first three is missing, daylight will make little contribution to the illumination of the space. Each of these factors is discussed in this chapter.

(d) Goals of Daylighting

Improved aesthetics, provision of human biological needs (circadian rhythms and visual relief), and reduction of electric lighting energy usage are the most important advantages of daylighting a building. Key goals in daylighting design are to provide sufficient illuminance, minimize the perception of glare, and provide for overall visual comfort.

8.2 HUMAN FACTORS IN DAYLIGHTING DESIGN

The following human-related factors (as opposed to the physical aspects of light) are described briefly to illustrate the importance of considering daylighting, and especially these factors, in the design of spaces.

(a) Windows and View

There is a common belief that if a window is placed in a wall, there will be sufficient view and daylight. The view function of a window, however, is very different from the daylighting function. The most preferred views from a window include the sky, the horizon, and the ground. In offices, people enjoy having windows in their work space because of the views. The functional advantage to a window is that people can look into the distance to reduce eye fatigue after doing close desk tasks. Depending upon the type of facility, the designer should be aware of special circumstances—for example, ensuring that bedridden occupants of care facilities have views from their vantage points, providing lower sills in facilities for children (depending upon safety), or accommodating people in wheelchairs by providing low-sill windows in bedrooms and other areas.

(b) Productivity and Satisfaction

Productivity is a complex issue that is difficult to isolate or attribute to a single parameter such as daylighting. The connection to the temporal qualities of daylight improves our psychological well-being and productivity. In studies of classrooms, windows, daylight, and performance, researchers found that students with more daylighting in their classrooms progressed faster on math and reading tests than students with less daylighting. Also, sources of glare negatively impact student learning, and the issues of control of windows, blinds, sun penetration, and acoustic conditions are important for teachers. In another study, retail stores were found to have a “daylight effect on increased monthly sales” (Heschong Mahone Group, 1999–2003).

(c) Controlling Daylight in Interior Spaces

Daylight, whether diffuse light or direct sunlight, provides significant benefits associated with psychological well-being. On the other hand, there are potential problems—such as glare or substantial cooling loads—caused by uncontrolled quantities and qualities of light. Direct sunlight is not, however, always a liability. In nontask areas, a momentary sunny patch, a streak of sunlight against a wall, or a series of multiple shapes provides visual interest and dynamism to a space. Sunlight in task areas can be controlled in a number of ways:

- Provide exterior fixed shades that exclude sunlight for all sun positions.
- Use systems that diffuse the incident sunlight sufficiently to eliminate glare potential.
- Provide occupant-controlled adjustable shades.

(d) Minimize Glare

Glare is a difficult problem to overcome when balancing daylight and view. Any window (including north exposures) can produce problematic glare if the window is within the field of view. High contrast ratios between a window and adjacent surfaces can occur unless the window is designed to reduce luminance ratios through the use of sunshading devices, lightshelves, high-reflectance interior surfaces, light-colored window surrounds and mullions, and low-transmittance glazing (though such glazing will reduce light flux through the window). Furniture should be oriented to work with sidelighting (as opposed to having an occupant face a window).

8.3 SITE STRATEGIES FOR DAYLIGHTING BUILDINGS

Optimal daylighting opportunities depend upon a building's position on a site relative to available daylight, horizon obstructions, orientation, and building form. The quality of daylight, its effects on illumination, and solar position for passive heating and control of cooling loads are of particular importance to the designer. Site obstructions such as neighboring buildings, trees, and landforms will determine the maximum available daylight on a site and the maximum project envelope that will preserve daylight access to adjacent properties (Fig. 8.2).

Orientation. In many locations, an ideal orientation for buildings is an elongated, narrow plan allowing the north and south façades of the building maximum exposure to more easily controllable daylight. From a daylighting standpoint, this is desirable because direct solar radiation received by the south façade is easier to control to prevent excess solar gain, is relatively uniform, and is necessary for passive solar heating strategies. The nearly constant diffuse skylight availability on the north façade is advantageous for uniform and soft daylighting. Figure 8.3 shows how orientation affects cooling, lighting, and heating energy for a building.

Zoning. Zoning considerations are among the most important influences on building form and external design, along with the familiar aesthetic, social, legal, economic, and technical influences that combine in a tug of war familiar to the building designer.

The thermal and luminous zoning of a building recognizes that different envelopes and support systems may be required around and within the building. The more carefully zoning is considered in these early design stages, the lower the building's annual energy consumption will be because of enhanced lighting and thermal performance. Zoning is one of the first steps to passive heating and cooling design.

Zoning is most often influenced by the following visual and thermal factors:

1. *Function.* Particularly important because of the variations in internal heat gains between functions, function may also influence the zonal organization of a building, as in Fig. 8.4. Comfort conditions may vary considerably between functions; air temperatures can be lower for a strenuous activity than for a sedentary activity, or heat tolerance may be greater for some activities (restaurant kitchens) than for others. Some functions thrive in daylight; others shun it. Some functions adversely affect the IAQ of other functions.
2. *Schedule.* Closely related to function, scheduling can influence both the envelope and the support system. An activity scheduled only between 9:00 A.M. and 4:00 P.M. can often be entirely daylit at a time when the outside temperatures are the warmest of the daily cycle. By contrast, an activity that takes place only from 9:00 P.M. to 4:00 A.M. will be entirely dependent on electric lighting, whose heat can be used to overcome the chill of the outside temperatures during these hours in winter. (In the summer, such heat can be flushed away with the cool outside night air in many U.S. locations.) Support systems are often divided by scheduling considerations: If one activity has operating hours different from those of the remainder of the building, a separate mechanical system is often provided. This saves energy, because large equipment will not be underused to provide heating or cooling for only one zone.
3. *Orientation.* The degree of exposure to daylight, direct sun, and wind is obviously important to zoning. Consider the block-square office building floors (Fig. 8.4) on a cold, sunny, and windy day. Perimeter spaces with direct sun through

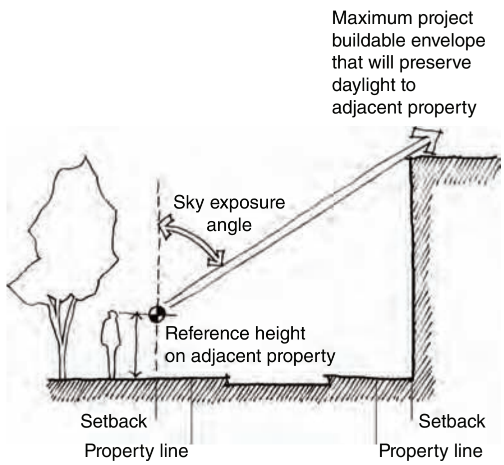


Fig. 8.2 *Protecting a site from obstructions to daylight. (Drawing by Erik Winter.)*

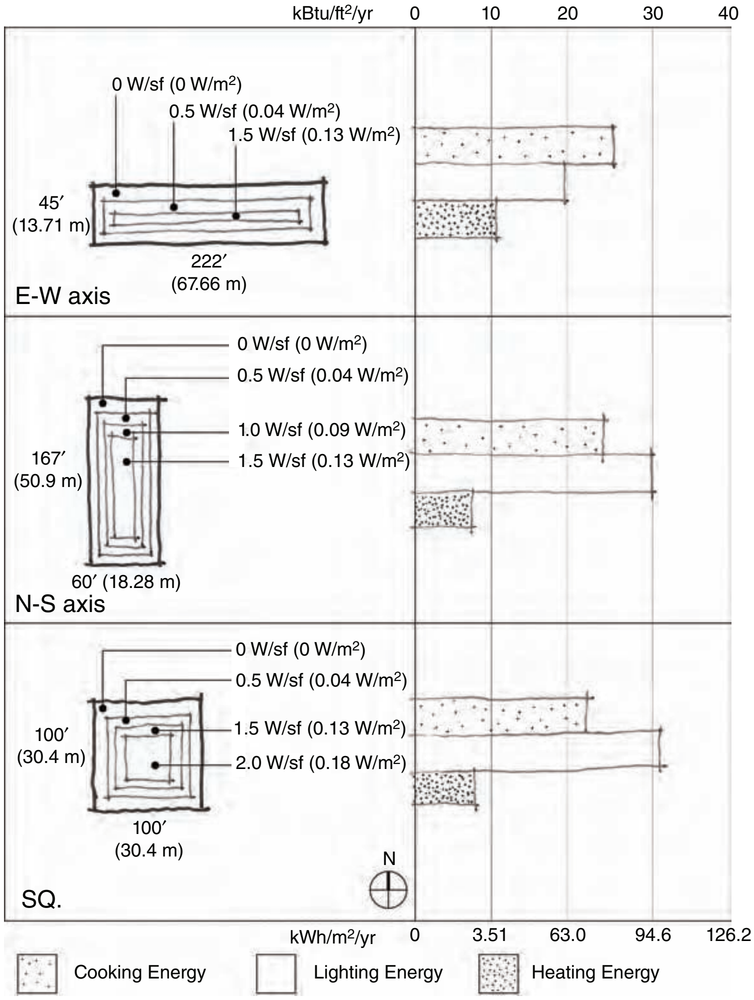


Fig. 8.3 *Effect of building orientation on energy consumption. (Drawing by Erik Winter after Moore,* Environmental Control Systems, *1993.)*

the windows may gain more heat than is lost and thus need cooling. This might be done by the opening of windows, but too much cold air (especially on the windy side of a building) may make occupants near the windows uncomfortable. Perimeter spaces without direct sun may have a net heat loss due to heat loss through glass, infiltration, and a lack of electric lighting (because daylight is adequate). These spaces will need heat from a mechanical support system. Interior (no-daylight) spaces are often overheated by electric lighting because they cannot lose heat. These spaces will need cooling from the support system.

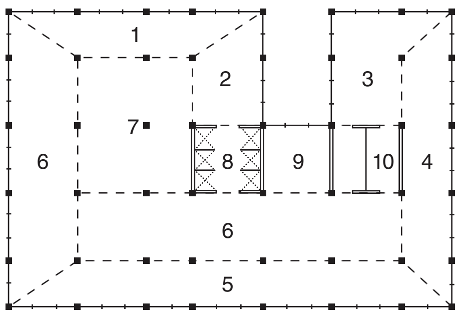


Fig. 8.4 *Daylight zoning for a mixed-use building with perimeter and internal zones as well as varying types of use. Scheduling and/or internal load differences within any one of these zones could require division into additional zones. (Drawing by Amanda Clegg.)*

Form. At its simplest, form can be reduced to questions of tall or short, thick or thin. Figure 8.5 compares these form variations to their impacts on heating, cooling, and daylighting solutions. Thicker, taller buildings have more floor space away from climate influences; being electrically lit rather than daylit, they generate heat and need cooling all year. These buildings are called *internal load dominated* (ILD). In contrast, thinner buildings—in which nearly all spaces have an exterior wall—need heating in cold weather and cooling in hot weather; electric lights by day are largely unnecessary. These buildings are called *skin-load dominated* (SLD).

The ultimate choice of building form is determined by a combination of design issues; the energy use issue can help in the selection process. Once the building form has been chosen, the functions can be distributed according to typical architectural criteria, including daylighting zoning.

In the selection of a building form, some particularly important questions accompany each energy use. Because the question of daylighting versus electric lighting frequently is so influential in determining whether heating or cooling will be the dominant concern, we begin with daylighting.

Daylighting Issues

1. What will be the relative emphasis on sidelighting (characterized by uneven distribution and glare in the visual field but little glare on horizontal surfaces) and toplighting (the reverse characteristics)?
2. What role will direct sun play in daylighting? In winter, can solar heat without glare be admitted?
3. How can seasonal adjustments be made in the size of daylight openings?
4. To what extent will daily changes in daylighting control be necessary?
5. How can adequate daylight be admitted in an even way, such that unwelcome dark-appearing places are avoided?

Heating Issues

1. Can the sun be used to heat spaces? If so, how will south-wall design be affected?
2. How can openings in walls facing other directions be kept to a minimum without daylight being shut out? Where such openings are desirable, how low a fenestration U-factor can be justified?
3. What role will direct sun through south glass or skylights play in daylighting?
4. How can daylight be admitted but the chilling effects of large, cold glass surfaces be minimized?
5. How can incoming fresh air be warmed before it chills the people sitting near the fresh air opening?
6. Is there surplus heat elsewhere in the building that can be used to help warm perimeter spaces?

Cooling Issues

1. Will the strategy be to open the building to breeze or close the building for coolth retention, or to use a combination of these alternatives (open by night, closed by day)?
2. How can direct sun be kept out of the building? Can east and west windows be minimized and adequate daylight still be provided?
3. How can adequate daylight be admitted for winter conditions without overlighting (and thus overheating) for summer conditions?
4. When can cooling be provided by outdoor air rather than by a refrigeration cycle?
5. Can the operation of refrigeration machinery be concentrated during the coldest (nighttime) hours, when electric power is cheapest?
6. How can incoming fresh air be cooled before it warms the people sitting near the fresh air opening?
7. Can the structure of the building be used to absorb heat by day, then be flushed with night air in climates with cool nights?

Establishing an appropriate building form in the early stages of design is critical to daylighting performance. The width of the long, narrow plan previously described will determine how much of the floor area will have access to usable daylight. Generally, a 15-ft (4.5-m) wide perimeter zone can be completely daylit; the next 15- to 30-ft (4.5- to 9.0-m) area can be partially daylit; and beyond 30 ft (9 m) will be electrically lit; the total of which can be used to determine the width of a building.

Envelope. The next design step involves relating the climate to the design of the building's skin. Each skin element provides an opportunity for thermal and luminous exchange between inside

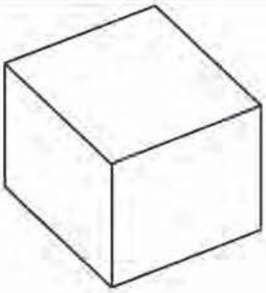
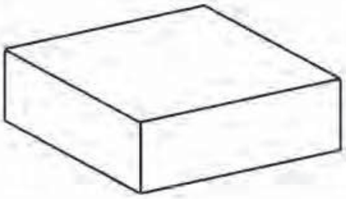
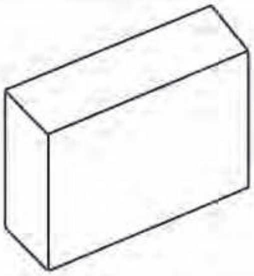
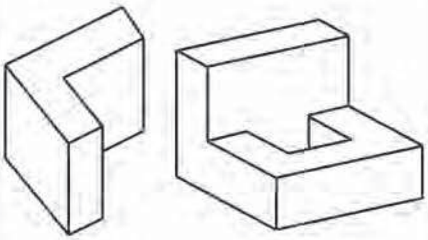
BUILDING TYPE	DAYLIGHT	HEATING	COOLING
 THICK TALL BUILDING	✓– Core is dark. Perimeter lighting is unidirectional	✓– Unbalanced solar gain makes perimeter zoning and control critical	✓– Large core requires mechanical cooling. Perimeter ventilates poorly
 THICK SHORT BUILDING	✓ Toplights and perimeter windows can provide adequate daylighting	✓ Passive heating systems may be implemented although somewhat limited and unbalanced	✓– Passive cooling possible but costly. No cross ventilation
 THIN BUILDING, TALL OR SHORT	✓+ Complete sidelighting for all spaces can be achieved	✓+ Passive heating and solar heat gain mitigation possible	✓+ Natural ventilation is easily accomplished
 THIN COMBO BUILDING	✓ Complete daylighting for most spaces	✓+ Passive heating and solar heat gain mitigation possible	✓+ Natural ventilation is easily accomplished

Fig. 8.5 *The effect of building form on environmental control strategies. The illustration shows how building layout affects cooling, daylighting, and heating opportunities. (Drawing by Nathan Majeski; based upon concepts presented in Figs. 8.1 and 8.2 of* Mechanical and Electrical Equipment for Buildings*, 10th ed.)*

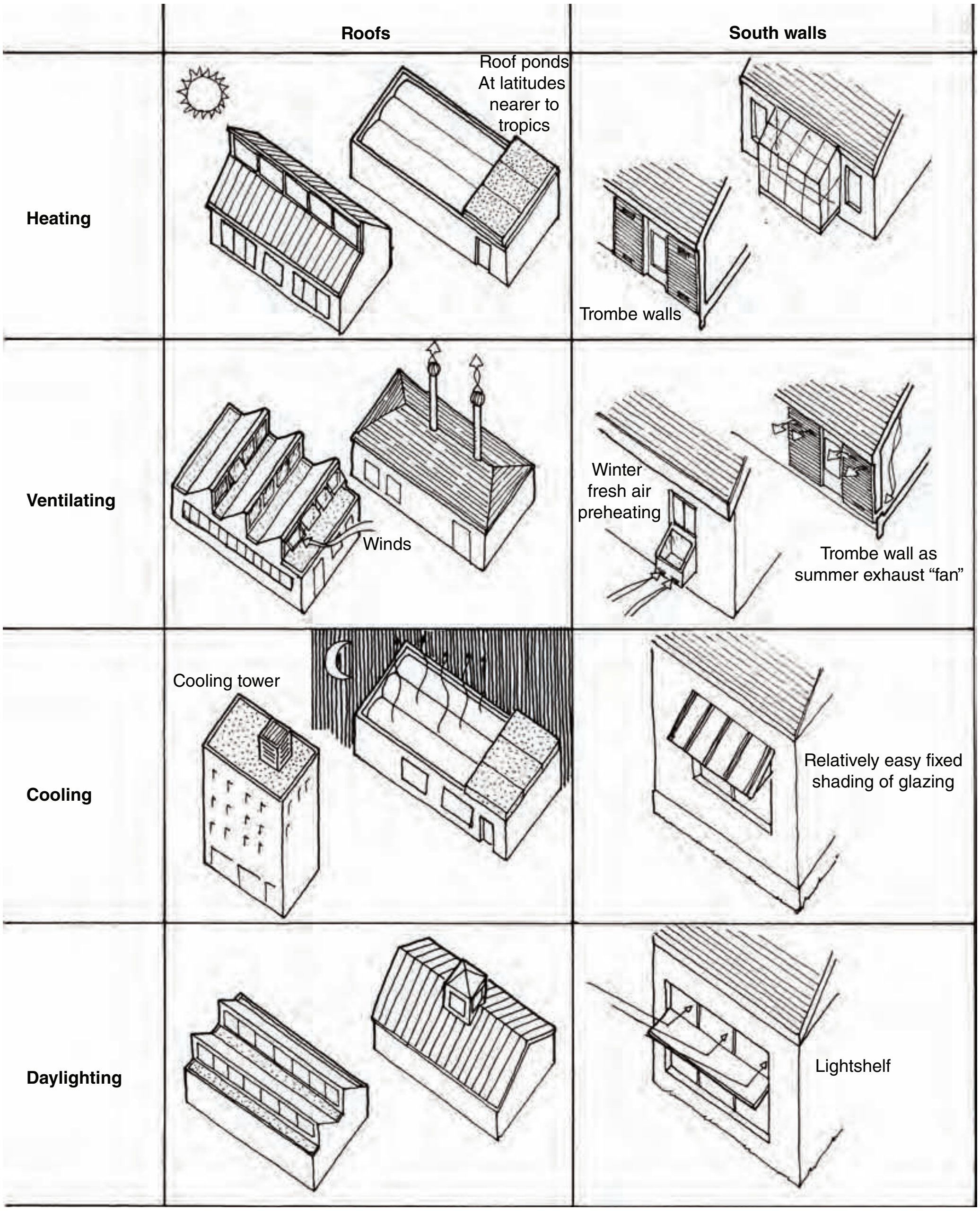


Fig. 8.6 *The components of a building's envelope can be used both to conserve energy and to admit on-site or natural energy sources.*

and outside; heating, cooling, ventilating, and daylighting devices can be mixed as needed. Figure 8.6 shows some of the most common of these devices for varying orientations. Sections in this chapter give numerical criteria for sizing these skin elements, with an emphasis on the use of on-site, renewable energy resources. These criteria may conflict with the size relationships that may be prescribed by codes and standards for conventional buildings.

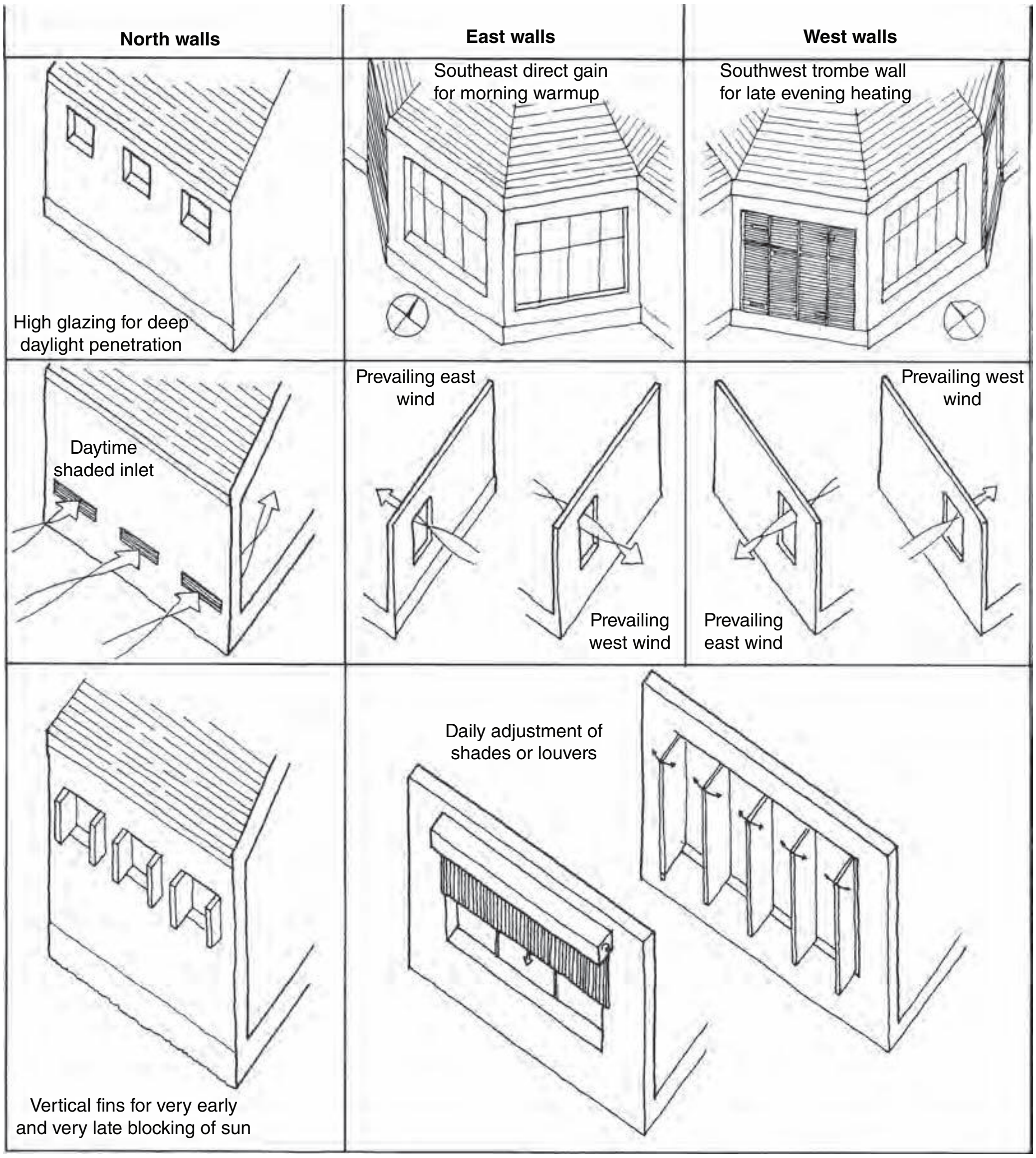


Fig. 8.6 *(Continued)*

Fenestration. Codes and standards typically prescribe a relationship between floor area and fenestration area (residential buildings) or total wall area and fenestration area (nonresidential buildings). These prescriptions assume that a building will be designed conventionally, that is, to rely on imported energy for lighting, heating, and cooling. Thus, prescribed areas of fenestration tend to be rather small. If a designer wishes to rely on daylighting to a greater extent, then some proof of benefit will be needed.

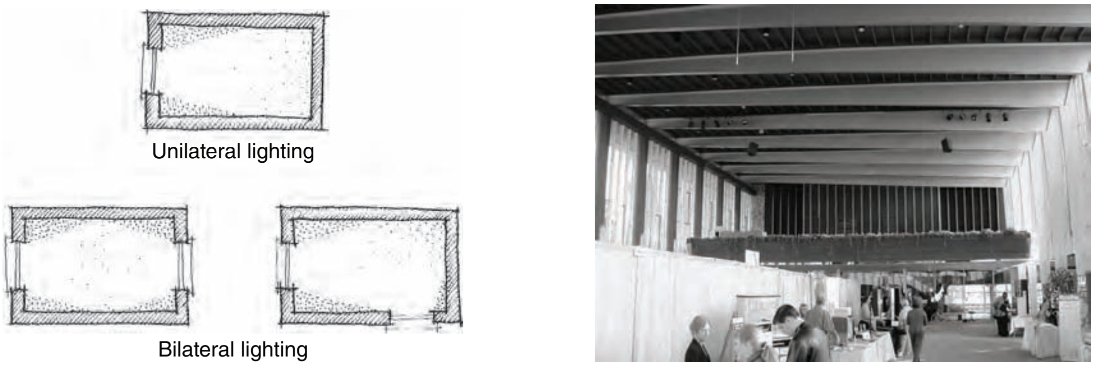
Daylighting is accompanied by large glass areas, which increase a building's heating needs in winter; yet in such buildings, less heat from electric lighting is available to fill those needs. Another complication is that adequate daylight requires much larger glass areas under dim winter skies than under bright summer skies. If the glass area is sized for winter daylighting, then excessive daylight—and, along with it, excessive heat—might be admitted in summer. With proper controls, daylighting can reduce summer cooling loads, relative to electric lights, but it will usually increase winter heating loads. Where passive solar heating or surplus heat from another source is readily available, this trade-off is attractive.

One of the earliest and most difficult questions for the designer is how much fenestration is optimum for a building. Some of the major energy end uses in buildings are: 30% for space heating, 11% for space cooling and ventilation, and 14% for electric lighting. By building type and location, however, this proportion of energy use can change substantially. Daylighting and the related square footage of windows can largely determine whether space heating or space cooling will be the dominant need within the building.

8.4 APERTURE STRATEGIES: SIDELIGHTING

Sidelighting systems admit light from apertures in window walls, and light sweeps across the space from one or more sides. The distance to which usable daylight penetrates a space and falls onto a work plane is the variable that designers work with to provide for sufficient illuminance. Generally, sidelighting is best for desk tasks because there are no veiling reflections, provided there is proper orientation of the worker. A number of generalized sidelighting strategies provide good illuminance fairly far into a space and improve visual comfort. The variety of approaches and components available to the designer is extensive. A complete discussion is provided in *Daylight in Buildings: A Source Book on Daylighting Systems and Components* (International Energy Agency, 2000). Schematic examples of a few typical design strategies are described below and in Figs. 8.7–8.14.

- Design for bilateral lighting: Daylight within a space is generally most evenly distributed when a space is lit from two walls (bilateral lighting), as shown in Fig. 8.7. Bilateral lighting from “opposite” walls produces the most evenly distributed lighting condition. Unilateral lighting (windows on one wall) can increase the potential for glare.
- Place windows high on a wall: In general, for a given window area, daylight will penetrate farther into a space and have more uniform distribution when windows are placed high on a window wall (Fig. 8.8). If possible, raise the ceiling height to accommodate a higher window position. Use the ceiling as a reflecting surface by placing window heads as close as possible to the ceiling.
- Use adjacent walls as reflectors: Interior walls become reflectors when windows are placed adjacent to them, thus reducing the contrasting edge around the window (Fig. 8.9). This arrangement can also bring visual delight if the reflecting wall is a light color, which will reveal patterns and colors from sunlight and reflect diffuse light farther into the space.
- Splay the walls of an aperture: This strategy is similar to the reflector strategy described previously, where light washes across a longer or rounded surface area around the window. When the edges of window openings are splayed (Fig. 8.10) or rounded, these illuminated surfaces surrounding the window reduce contrast and are more visually comfortable, thereby reducing the potential for glare.
- Provide daylight filters: Daylight may be modified (either blocked or diffused) by a number of elements, which include trees, vines, and trellises (Fig. 8.11) on the exterior of a building; filters for the interior of a building may include blinds, drapes, or translucent glazing.
- Provide summer shading: Depending upon passive solar heating and cooling design strategies, in some instances direct sunlight should be blocked before it enters a space at certain times of the year. Figures 8.12–8.14 show examples of exterior louvers (horizontal or vertical), overhangs, trellises, trees, and lightshelves that can block direct sunlight, reflect diffused sunlight into a space, and provide solar control. Light-colored materials or finishes on these components will reduce contrast between the element and the view or sky beyond. Lightshelves that also serve as a shading device can be designed as a horizontal (integrated or attached) component positioned inside and/or outside a window. Typically above eye level, they divide a window into a lower view portion and an upper area exclusively for daylight.

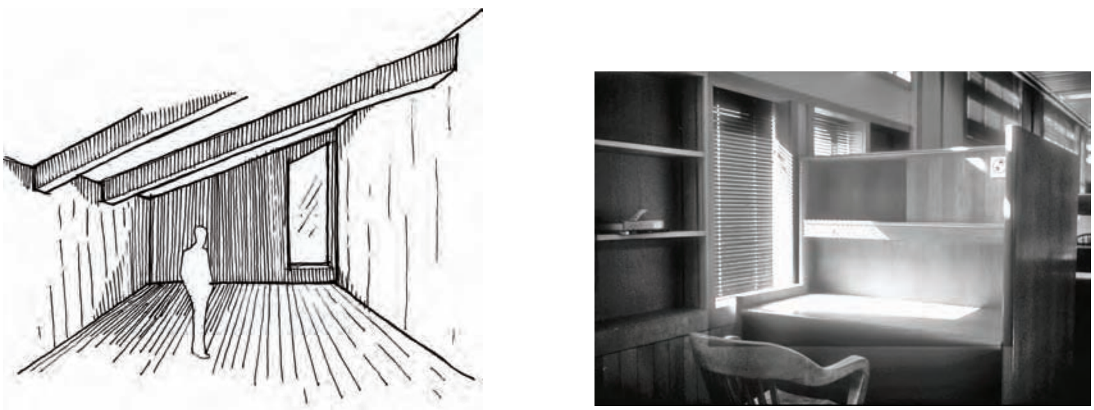


(a) (b)

Fig. 8.7 *(a) Plan diagrams of unilateral and bilateral daylighting. (b) Windows on two sides (a bilateral approach) at the Crystal Cathedral campus, Anaheim, California. (Drawing by Erik Winter; photo by Alison Kwok; © Alison Kwok; all rights reserved.)*

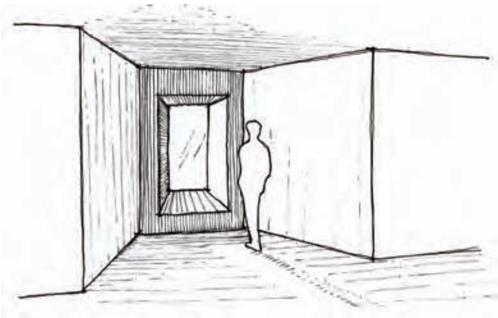
(a) (b)

Fig. 8.8 *(a) With higher windows, daylight extends farther into a space. (b) High windows in a classroom at the University of Oregon. (Drawing by Erik Winter; photo by Nathan Majeski.)*



(a) (b)

Fig. 8.9 *(a) Windows adjacent to a wall provide an additional reflecting surface. (b) Reading carrel adjacent to a window at the Graduate Theological Union Library, Berkeley, California. (Drawing by Erik Winter; photo by Alison Kwok; © Alison Kwok; all rights reserved.)*



(*a*)

(*b*)

Fig. 8.10 *(a) Splayed window and wall provide additional reflecting surfaces. (b) Splayed window opening to increase visual comfort and reduce glare potential at the 2011 Solar Decathlon EMPOWER House by The New School and Stevens Institute of Technology. (Drawing by Erik Winter; photo by Alison Kwok; © Alison Kwok; all rights reserved.)*

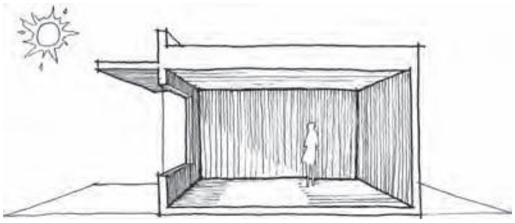
(*a*)

(*b*)

Fig. 8.11 *(a) Trellis at Westcave Environmental Center, Round Mountain, Texas. (b) Several layers (trees, shading, curtains) at a window can filter light and provide shade. (Photo by Walter Grondzik; © Walter Grondzik; all rights reserved; Photo by Nathan Majeski.)*

8.5 APERTURE STRATEGIES: TOPLIGHTING

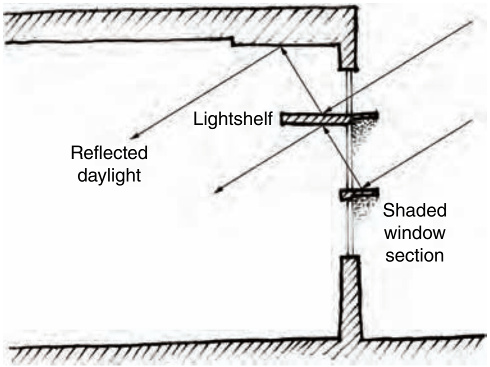
Skylights, roof monitors, and clerestories are suitable aperture strategies for the top floor of a building, particularly for interior locations of large floors that are far from perimeter windows. To prevent veiling reflections or direct glare situations, toplighting components should be placed away from the *offending zone* (areas with a direct view from an occupant), or a baffle or interior reflector should



(a)

(b)

Fig. 8.12 *(a) Horizontal overhangs block light but also act as a reflector for light from the ground plane. (b) Horizontal shading devices at Ash Creek Intermediate School, Monmouth, Oregon. (Drawing by Erik Winter; photo by Alison Kwok; © Alison Kwok; all rights reserved.)*



(a)

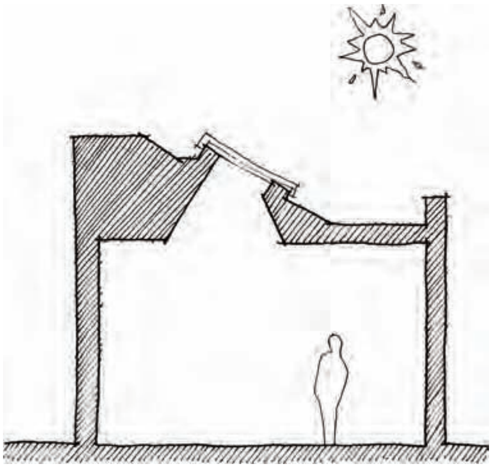
(b)

Fig. 8.13 *(a) Lightshelf reduces the daylight factor near a window and increases it at greater depths. Shelf material (opaque, translucent) and angle of installation (horizontal, sloped up) markedly affect performance. (b) Classroom lightshelf, Allen Hall School of Journalism, Eugene, Oregon. (© Karen Tse; used with permission.)*

Fig. 8.14 *Fixed horizontal louvers on the south façade at the Phoenix Public Library, Phoenix, Arizona. (© Walter Grondzik; all rights reserved.)*

be used to diffuse and control daylight. Most of the strategies for sidelighting also apply to toplighting, several of which are discussed here.

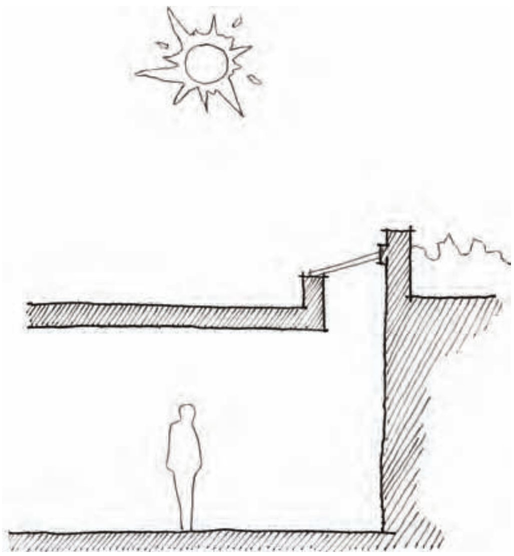
- Splay the "walls" of an aperture: Splaying the sides of a skylight makes the skylight appear larger because light washes along a larger surface area and reflects diffuse light into the space (Fig. 8.15). This strategy reduces the potential for glare similarly to the way splayed windows function.
- Place toplights high in the space: Higher ceilings with skylights allow more surface area for light to diffuse upon, virtually becoming a larger source (Fig. 8.16). This strategy works well in spaces where the skylight is well above the field of view.



(*a*)

(*b*)

Fig. 8.15 *(a) Splayed surfaces of a skylight provide areas for diffusely reflected light. (b) Conical skylights at Millesgården Museum and Sculpture Garden, Lidingö, Sweden (Everet Milles, 1955). (a) Drawing by Erik Winter; (b) © Karen Tse; used with permission.*

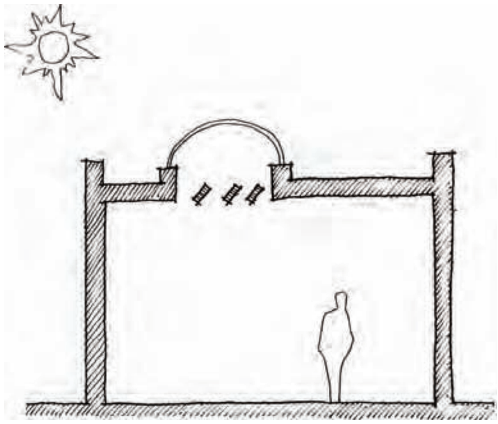


(*a*)

(*b*)

Interactive Animation

Fig. 8.16 *(a) A skylight near a north wall provides reflecting surfaces for uniform light distribution and reduces the potential for glare. (b) The linear toplight enables light to wash an interior concrete wall at the Chapel of the Holy Cross, Turku, Finland (Pekka Pitkänen, 1967). (a) Drawing by Erik Winter; (b) © Karen Tse; used with permission.*



(*a*)

(*b*)

Fig. 8.17 *(a) Skylight with baffles that block direct solar radiation. (b) Baffled skylight daylighting design at Mt. Airy Public Library, Mt. Airy, North Carolina (Edward Mazria, 1984). (Drawing by Erik Winter; photo by Fuller Moore; © 2004 The Society of Building Science Educators; used with permission.)*

- Use interior devices to block, baffle, or diffuse light: Direct sunlight can be redirected by a reflector below a skylight, clerestory, or roof monitor that, depending upon the surface material, diffuses the light onto another surface within the space (Figs. 8.17 and 8.18).

Fig. 8.18 *Clerestory skylights with louvers at the U.S. Holocaust Memorial Museum in Washington, DC (Pei, Cobb, Freed & Partners, 1993). (© Alison Kwok; all rights reserved.)*

8.6 SPECIALIZED DAYLIGHTING STRATEGIES

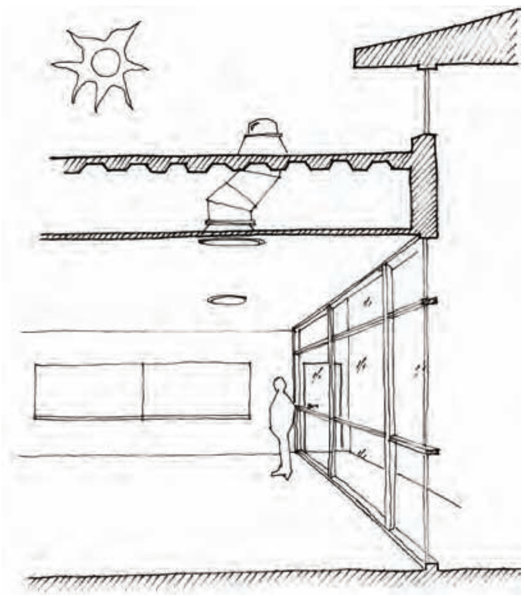
A number of innovative daylighting systems can be categorized as experimental, yet they have tremendous potential. Some of these strategies include laser-cut or prismatic panels, fiber optics, solar tubes, and heliostats. More advanced systems use reflectors and lenses to introduce concentrated luminous energy into some type of light-conducting device. These may be fiber-optic bundles, prismatic light pipes, or some type of mirrored channel. The problem of heat rejection becomes more severe as the degree of solar energy concentration increases. Thus, light pipes are much less critical in this regard than are optical-fiber systems. The efficiency and economic feasibility of these systems are interdependent because of the materials used; the farther the light is transmitted, the lower the system's overall efficiency and the higher the cost to make the system technically feasible.

Light pipes. This term refers to several strategies: daylight pipes, electric light pipes, and fiber-optic pipes (Fig. 8.19). The light pipe operates by collecting light through a heliostat; channeling daylight (or electric light) through a reflective tube made of prismatic glass, plastic film, and mirrors; and diffusing light at the end of the pipe. It is an exciting strategy because of the length it can transport light—65 ft (20 m)—from a single-point light source.

(*a*)

(*b*)

Fig. 8.19 *(a) Heliostat on the rooftop of a building tracks the sun and directs light into an 8-ft (2.4-m) wide atrium and down 14 floors. (b) The heliostatic light tube is a 120-ft (37-m) long, 6-ft (1.8-m) diameter, 12-sided steel-and-aluminum frame—enclosing laminated glass panels and surrounded by fabric—within the atrium at the Morgan Lewis building in Washington, DC. (© Carpenter Norris Consulting; used with permission.)*



(*a*)

(*b*)

Fig. 8.20 *(a) Skylight through a roof structure. (b) Top of Solatube® skylights on the roof at Ash Creek Intermediate School in Monmouth, Oregon. (Drawing by Karen Tse; photo © Alison Kwok; all rights reserved.)*

Tubular skylights. These light shafts have highly reflective surfaces and are capped by a clear skylight (Fig. 8.20). The amount of light transmitted and delivered varies with the diameter of the shaft. They are convenient and economical for supplemental illumination in hallways, closets, and areas without a need for a lot of control. The light quality is comparable to that of a ceiling-mounted fluorescent fixture (often indistinguishable).

8.7 BASIC CHARACTERISTICS OF LIGHT SOURCES

For daylighting design a good understanding of light sources, characteristics of light, sky conditions, and lighting "behavior" will optimize the daylighting goals of the project. Technological developments in the lighting industry offer the designer a variety of energy-efficient and environmentally responsible sources and controls to fully integrate daylight and electric light into the design process (Fig. 8.21).

Daylight sources may be categorized as direct (direct sunlight or diffuse skylight) or indirect (light reflected or modified from its primary source). *Efficacy* is a basic characteristic common to daylight (and electric light) sources—measured in lumens per watt (lm/W). Efficacy is the ratio of lumens provided, to watts of heat produced by a light source. Table 8.1 lists efficacies of common light sources. Due to its high efficacy, daylight introduces less heat per lumen than electric sources, making use of daylight an attractive strategy for reducing cooling loads in buildings caused by lighting (assuming effective, balanced distribution and utilization of illumination).

TABLE 8.1 Efficacy of Various Light Sources

Source	Efficacy (Lm/W)
Candle	0.1
Oil lamp	0.3
Original Edison lamp	1.4
1910 Edison lamp	4.5
Incandescent lamp (15–500 W)	8–22
Tungsten–halogen lamp (50–1500 W)	18–22
Fluorescent lamp (15–215 W)[a]	35–80
Compact fluorescent lamp[b]	55–75
Mercury-vapor lamp (40–1000 W)[a]	32–63
Metal–halide lamp (70–1500 W)[a]	80–125
High-pressure sodium lamp (35–100 W)[a]	55–115
Induction lamp[c]	48–70
Sulfur lamp[c]	90–100
Direct sun (low altitude = 7.5°)	90
Direct sun (high altitude > 25°)	117
Direct sun (mean altitude)	100
Sky (clear)	150
Sky (average)	125
Global (average)	115
Maximum source efficacy predicted (in the year 2010)	150
Maximum theoretical limit of source efficacy	250 (approximate)

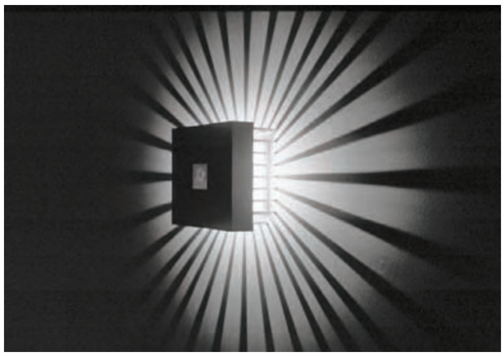
[a]Includes ballast losses (with electronic ballasts, lumens per watt become much higher). Losses vary between ballasts and manufacturers.

[b]With electronic ballasts.

[c]With a power supply.

The efficiency of a standard incandescent lamp in converting electrical energy to light is approximately 7%; the other 93% is released as heat. Fluorescent lamps are approximately 22% efficient,

(*a*)



(*b*)

Fig. 8.21 *(a) A daylit space; sunlight streams through a window at the Santa Anna Monastery in Santa Anna, Italy. (b) An electrically lit space—a wall sconce at the Westin Peachtree Plaza hotel in Atlanta, GA. (© Alison Kwok; all rights reserved.)*

and although they are a great improvement over incandescents, the generally low efficacy of lighting in buildings accounts for a large proportion of building energy use. Consequently, selecting light sources for buildings—whether daylight or electric light (or, more likely, a combination of both)—involves simultaneous lighting and thermal considerations. Because electric lighting in American nonresidential buildings consumes 25% to 60% of the electric energy utilized, any attempt to reduce this quantity must necessarily include integration of the cheapest (insofar as energy is concerned), most abundant, and, in many ways, most desirable form of lighting available—daylight. In selecting appropriate light sources for buildings, understanding the characteristics of the light sources will allow a designer to use them appropriately for energy efficiency and to provide visual and thermal comfort. For resource efficiency, a designer should first optimize daylight sources through building geometries and material finishes, and then design the electric lighting system to supplement and enhance illumination and effect.

8.8 SKY CONDITIONS

The most prominent characteristic of daylight is its variability. The source of all daylight is the sun. Exterior illumination, at a particular place and time, depends upon (a) solar position, which can be determined if the latitude, date, and time of day are given, (b) weather conditions (e.g., cloud cover, smog), and (c) effects of local terrain (natural and built obstructions and reflections). The position of the sun in the sky is expressed in terms of its altitude above the horizon and its azimuth angle. For all latitudes in the northern hemisphere, the sun's altitude is highest in summer, lowest in winter, and in between in spring and fall. Azimuth angle is defined as the sun's horizontal position angle, measured from the *south*. Solar position is absolutely predictable for any given time and location.

Cloud cover, unlike solar position, is only statistically predictable, on the basis of extensive U.S. Weather Service observations at numerous weather stations throughout the United States. At locations other than those for which recorded data are available, an educated guess is necessary. Outside the United States, a designer must rely on locally available data, which are often difficult to obtain.

The third factor—local terrain and construction conditions that either reduce illumination by shadowing or increase it by reflection—can be considered only on a case-by-case and site-specific basis.

For manual calculation procedures, it is sufficient to establish four basic sky conditions. These are:

1. Solid overcast sky
2. Clear sky without sun (in the field of view)
3. Clear sky with sun
4. Partly cloudy sky

(a) Standard Overcast Sky

This condition, which occurs for much of the year in northerly climates such as England, Scandinavia, and the Pacific Northwest, is called the *CIE sky*, because it was adopted by the Commission Internationale de l'Eclairage (CIE) as the standard design sky for daylighting calculations (CIE, 1970). This sky, as defined by the CIE, has a nonuniform brightness distribution, increasing from horizon to zenith in approximately a 1:3 ratio. Sky luminance at any altitude angle above the horizon is defined in Equation 8.1 as

$$L_A = L_Z \frac{1+2\sin A}{3} \tag{8.1}$$

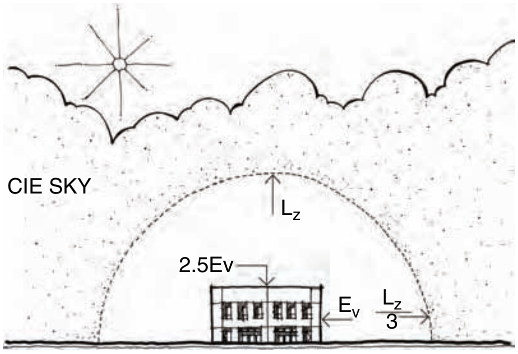
where
L_A = luminance at $A°$ above the horizon (in any direction)
L_Z = luminance at the zenith

Thus at the horizon, where $A = 0°$,

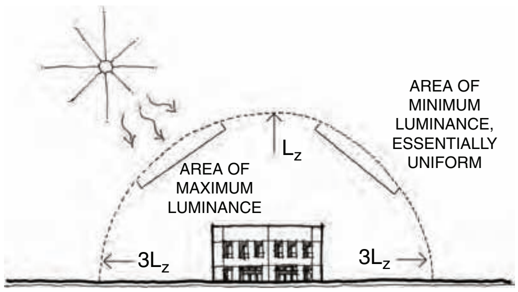
$$L_A = \frac{L_Z}{3}$$

The illuminance (density of light in lux) on unobstructed exterior horizontal and vertical surfaces produced by this luminance distribution has an approximate ratio of 2.5:1 (Fig. 8.22). This results from an integration of Equation 8.1 over the whole sky.

There is agreement among all sources that with an overcast sky, exterior horizontal illuminance varies directly with the sun's altitude, *irrespective of azimuth*. Various formulations for this relationship



COMPLETELY OVERCAST SKY:
(NONUNIFORM LUMINANCE)
(*a*)



CLEAR SKY:
(NONUNIFORM LUMINANCE)
(*b*)

Fig. 8.22 *(a) The completely overcast sky has a zenith luminance L_Z, which is 3 times the horizon luminance. With such a sky, illuminance on unobstructed exterior horizontal surfaces (E_H) is about 2½ times that on similar vertical surfaces (E_V). (b) The clear sky has the area of brightest luminance around the sun. The area opposite the sun is darkest and can be considered as essentially uniform at approximately 3500 cd/m² (1000 fL). (Redrawn by Erik Winter.)*

have been put forward. One formulation that gives good agreement with observations is by Krochman (1963), shown in Equation 8.2:

$$E_H = 300 + 21{,}000 \sin A \qquad (8.2)$$

where E_H is exterior horizontal illuminance (lux) and A is the solar altitude, in degrees. Solar altitude (and azimuth) for various times of day can be obtained from Table D.1. Figure 8.23 is a plot of year-round averages for both vertical and horizontal illuminance from an overcast sky as a function of solar altitude, based on U.S. Weather Service observations.

It is interesting to compare the exterior horizontal illuminance obtained from the two sources given: Krochman's formula (Equation 8.2) and the observation-based data of Fig. 8.23, for a few typical conditions. Solar altitude is obtained from Table D.1.

Latitude:	38°
Solar Time:	10:00 A.M.
Dates:	Dec. 21, March/Sept. 21, June 21

	Eq. 8.2	Fig. 8.23
Dec 21	8500 lux (790 fc)	8608 lux (800 fc)
Mar/Sept 21	14,623 lux (1359 fc)	15,923 lux (1480 fc)
June 21	18,669 lux (1735 fc)	23,134 lux (2150 fc)

The degree of agreement is generally satisfactory, and either source will yield suitable results.

One of the most convenient ways of expressing the quantity of daylight illuminance during the schematic design of buildings is the concept of *daylight factor* (primarily intended for overcast skies). Daylight factor is the ratio of indoor illuminance to available outdoor illuminance. Daylight factor is discussed in Section 8.13 as a means of setting criteria for, and determining the effectiveness of, a daylighting design.

(b) Clear Sky With and Without Sun

Horizontal Illuminance. Exterior horizontal illuminance on a cloudless day consists of two source components: diffuse illumination from the entire sky plus the much larger component of direct sunlight. As with overcast sky, various empirical formulas for both components have been proposed, and here too, all sources agree that the total illumination, diffuse plus direct, varies directly with solar altitude.

Figure 8.24 gives values for both components of exterior horizontal illuminance based upon observations. The *sky only* values are used to determine shaded skylight illuminance or daylong ground illuminance outside a shaded window—that is, a north-facing window, or an east/west window when the sun is on the opposite side of the building. In determining ground illuminance, the values given in Fig. 8.24 must be reduced somewhat, because they represent unobstructed horizontal illuminance, whereas the area outside a building window is partially obstructed from sky light by the building itself. If a building is so large that the ground outside the shaded window

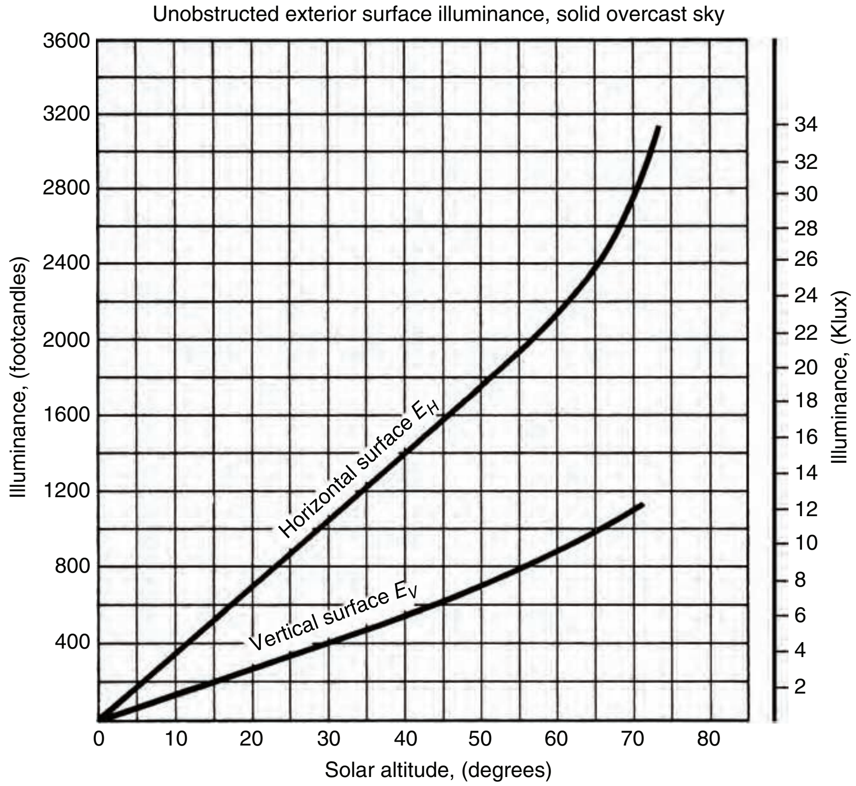


Fig. 8.23 *Curves giving unobstructed exterior surface illuminance directly from an overcast sky. (Data based on U.S. Weather Service observations; courtesy of Libbey-Owens-Ford.)*

effectively receives diffuse radiation only from the half of the sky away from the sun, an average figure for E_H of 1000 fc (~10,000 lux) can be used. This is because the luminance of the half of the sky away from the sun varies from a minimum of approximately 300 fL (1031 cd/m^2) for the deep-blue patch directly opposite the sun to about 2000 fL (6874 cd/m^2) at the sides, giving an average half-sky luminance of about 1000 fL (~3400 cd/m^2). This, in turn, gives a horizontal illuminance E_H, diffuse, of about 1000 fc (~10,000 lux) (see Fig. 8.22).

Figure 8.24 also gives horizontal illuminance from the sun only, as a function of solar altitude. This value, when combined with the proper portion of diffuse illuminance, as discussed previously, is useful in determining ground illuminance outside a sunny building exposure, or illuminance on an unshaded skylight. The light incident on an external reflector or lightshelf at a window can also be determined from these figures.

Vertical Surface Illuminance. Inasmuch as most daylighting is accomplished via vertical fenestration, vertical surface illumination is the major component of interior daylight. It is also important for determining the daylight contribution of vertical elements in skylights. There is no simple relationship between horizontal and vertical illuminance from a clear sky, as there is for an overcast sky, because the illumination on a vertical surface depends upon solar azimuth as well as altitude. More specifically, it depends upon the *bearing angle* (Fig. 8.25), which is defined as the horizontal angle between a vertical plane containing the sun and a plane perpendicular to the vertical surface in question. A bearing angle of 0° indicates that the sun plane is perpendicular to the vertical surface. Like E_H, E_V (vertical illuminance) is divided into two components: sky only and direct sun only, as plotted in Fig. 8.26 as a function of solar altitude and bearing angle. The *sky only* component is effectively

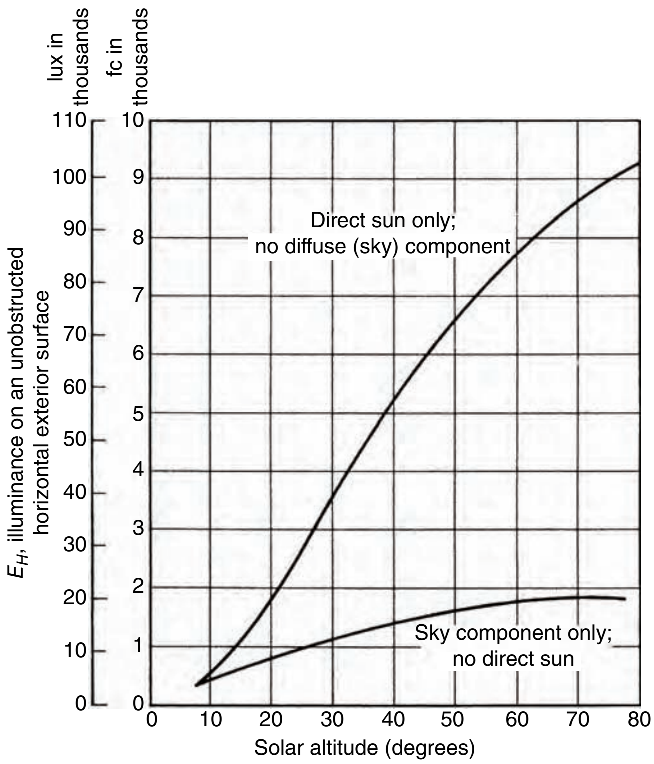


Fig. 8.24 *Components of the exterior horizontal illuminance on an unobstructed surface, from a clear sky, as a function of solar altitude. Total illuminance E_H is the sum of the two components. (From data in Rennhackkamp, 1967.)*

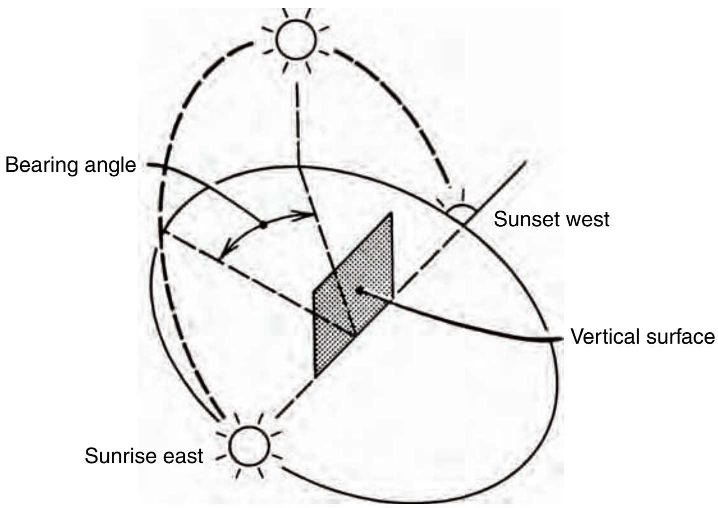


Fig. 8.25 *The bearing angle of a vertical surface—the angle between a hypothetical vertical plane perpendicular to the surface (say, a window) and a hypothetical vertical plane containing the sun. (Other sources refer to this angle as the window-to-sun azimuth angle or surface azimuth.)*

for the half-sky because a vertical surface can be exposed to a maximum of only half of the full sky. Solar radiation data may be translated into illuminance by using average "efficiency" figures for solar energy in units of lumens per watt of received radiation (Fig. 8.26).

(c) Partly Cloudy Sky

The luminance of a partly cloudy sky cannot be expressed mathematically because of its infinite variability of conditions. However, statistical data on cloud cover are available from observations at many weather stations, and these data should be used in computer-calculated, hour-by-hour energy analysis programs. For the purpose of lighting design, it is important to note that the illumination from a partly cloudy sky is *higher* than that from a clear sky by 10% to 15% because of additional reflected

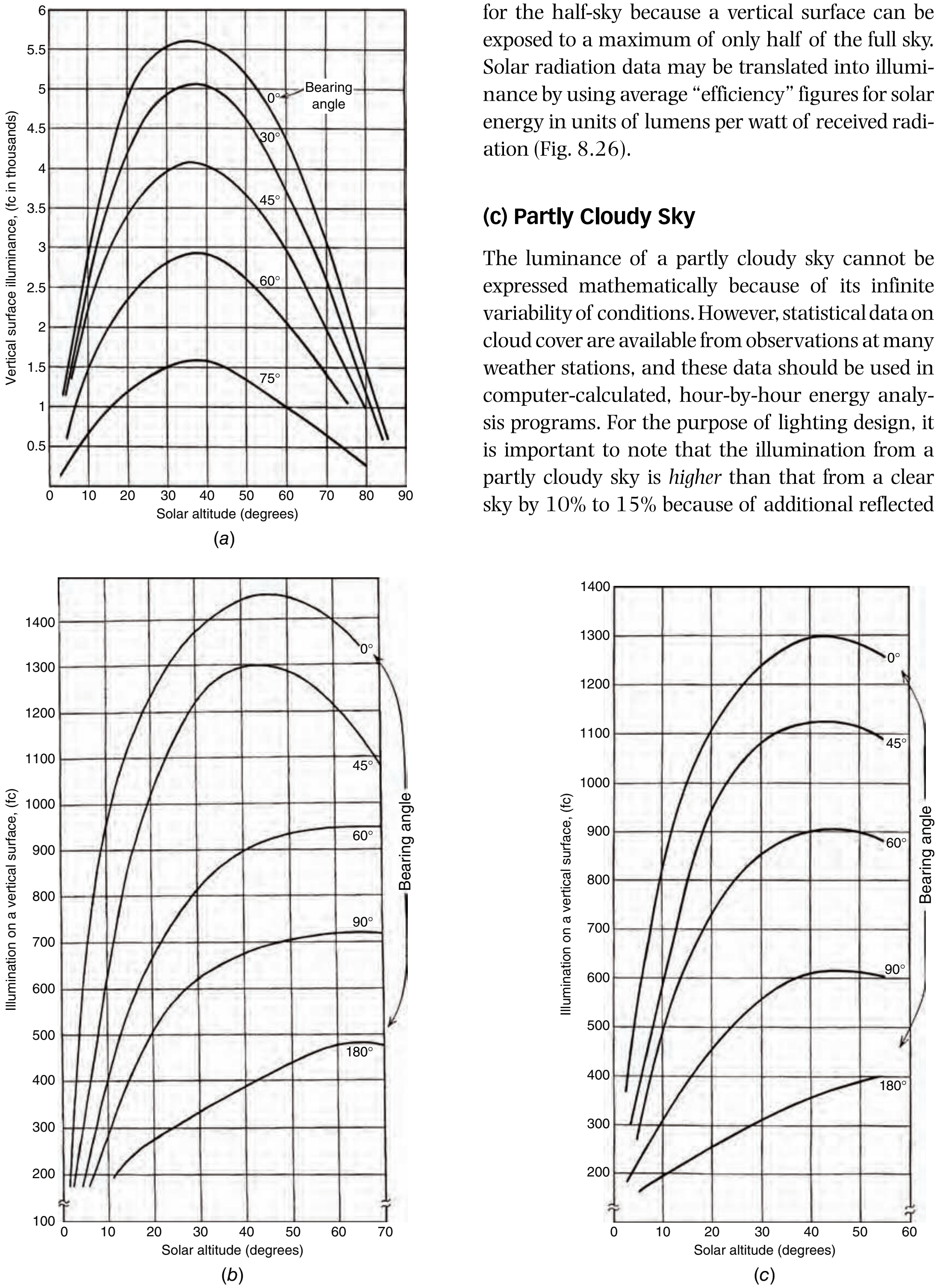


Fig. 8.26 *(a) Vertical surface illuminance, year-long average, sun only, no sky contribution. (b) Vertical surface illuminance, clear summer sky, no sky contribution. (c) Vertical surface illuminance, clear sky during various seasons, no sky contribution. (Courtesy of Libby-Owens-Ford.)*

sunlight from cloud edges. Several attempts have been made to account for this type of sky in terms of the effect on the daylight factor within a room, but none has received general acceptance.

8.9 DAYLIGHT FACTOR

When a building is designed to rely on daylighting, a prime design concern is the *daylight factor* (DF), which is expressed as the ratio of interior illuminance (E_i) to available outdoor illuminance (E_H) *under overcast skies.*

$$\mathrm{DF} = \frac{E_i \text{ indoor illuminance, at a given point}}{E_H \text{ outdoor illuminance}} \times 100\% \tag{8.3}$$

where E_H is the unobstructed horizontal illuminance. The daylight factor concept is applicable only where the sky luminance distribution is known or can reasonably be estimated. The Commission Internationale de l'Eclairage (CIE) defines an overcast sky and a clear sky whose luminance distributions are fixed for the purpose of calculations. Daylight factor cannot be used with skies with constantly changing luminance (partly cloudy and direct sun) because under such conditions the daylight factor at a given point also varies continuously, making the concept useless as a calculation tool *for absolute daylight values*.

Daylight factor as a means of expressing interior daylight illuminance is both absolute and relative. With a given sky luminance distribution, variations in daylight illuminance *inside* correspond exactly to variations *outside* (i.e., the daylight factor remains the same). This assumes a minimal effect from obstructions and ground reflections. Thus, the daylight factor allows determination of interior daylight distribution for varying fenestration, spatial arrangement, and building orientation.

Daylight factor is constant for a given space and window configuration. Interior illuminance can easily be calculated by knowing the daylight factors for locations in a given space and the exterior illuminance derived from sky luminance data. Daylight design analysis can use a combination of minimum exterior illuminance and corresponding minimum daylight factor requirements to predict daylight sufficiency under almost all exterior conditions.

8.10 COMPONENTS OF DAYLIGHT

Understanding the components of daylight is important to the design of apertures and the selection of materials. Daylight illuminance in a building consists of three components (see Fig. 8.27):

1. Sky component (SC)
2. Externally reflected component (ERC)
3. Internally reflected components ($\mathrm{IRC}_1 + \mathrm{IRC}_2$)

DF is the sum of these three components, each calculated individually for each location being considered. DF is a ratio, but the value of a given DF is based upon contributions from these components: DF = SC + ERC + IRC.

The *sky component* (SC) is that portion of total daylight illuminance at a point received directly from the area of the sky *visible through* an aperture. As the SC represents *received* light, it takes into account reductions due to window obstructions (mullions, etc.) and losses in transmission; that is,

$$\mathrm{SC} = \text{incident skylight} - \text{window losses}$$

The *externally reflected component* (ERC) represents light reflected from exterior obstructions onto the point under consideration. This *does not include ground-reflected light.* ERC is of significance only in built-up areas (where there are structures opposite an aperture) and can be estimated as the portion of the SC for that area of obstructed sky, reduced by the percentage of the sky obstructed (RD) and the *reflectance factor* (RF) of the obstruction; that is,

$$\mathrm{ERC} = \mathrm{SC} \times \mathrm{RD} \times \mathrm{RF}$$

Thus, if 25% of the sky is obstructed by a building with a 20% RF, we have

$$\mathrm{ERC} = \mathrm{SC} \times 0.25 \times 0.20$$

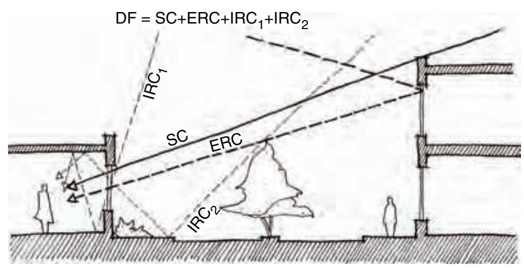


Fig. 8.27 *Total daylight factor (DF) is composed of the SC, ERC, and IRC. The IRC, in turn, is subdivided into reflected sky light and reflected ground light components. Note that surfaces deep in the room are illuminated with re-reflected light. (Drawing by Erik Winter.)*

For this particular example, then

$$\text{ERC} = 5\% \text{ of SC}$$

to be added to the remaining 75% of SC (25% of the sky was obstructed).

The *internally reflected component* (IRC) represents the light received at the point under consideration that has been reflected from interior surfaces. IRC is subdivided into reflected skylight (IRC_1) and reflected ground light (IRC_2). IRC_2 is generally small, and IRC $\cong$ IRC_1. IRC is, therefore, primarily dependent upon interior surface reflectances and upon the amount of window glazing, and becomes a large portion of DF deep within an interior space (see Table 8.2 for wall reflectance factors and Fig. 8.28 illustrating IRC as a function of the amount of glazing). IRC is normally calculated using published interreflectance tables, because direct calculation is extremely complex.

Typical curves for both horizontal and vertical daylight factors for a room with single (unilateral) sidelighting (windows on one side) are shown in Fig. 8.29. These curves are produced by a longhand daylight-protractor-aided technique (Building Research Station, London). Any change in parameters, such as window dimensions or height above the working plane, ceiling height, surface reflectance, ground reflection, and obstructions, alters these curves and requires recalculation and replotting. Exact calculation of even a few variants for a space is a tedious and time-consuming procedure.

The following manual methods describe alternative approaches available to save time and increase accuracy:

1. Use of simplifications, such as standard curves, tabular data, or the CIE method
2. Use of a library of graphic light distribution plots with varying parameters
3. Use of a less-laborious manual calculation procedure (one such technique is known commonly as the *lumen method* or the *IES method*)
4. Use of computer simulation software

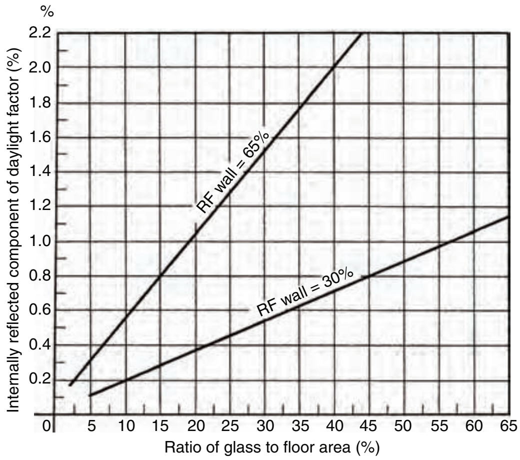


Fig. 8.28 *Plot of the IRC of the daylight factor as a function of amount of glazing, expressed as per DF (i.e., as a percentage of exterior illuminance). As expected, the effect of a lighter wall finish becomes more pronounced as the fenestration area increases.*

Designers may use daylight factor criteria as a starting point for daylight design, translating the DF values (such as those given in Table 8.3) into actual illuminances in footcandles (lux) and comparing the results to recommended illuminance values. The U.S. Green Building Council (USGBC) promotes a Leadership in Energy and Environmental Design (LEED) certification for buildings. Prior

TABLE 8.2 Effect of Wall Reflectance Factor on the Proportion of IRC in the DF

	30% Wall Reflectance		60% Wall Reflectance	
Distance from Window in ft (m)	Total DF	$\frac{IRC}{DF}$ (%)	Total DF	$\frac{IRC}{DF}$ (%)
0	30	1	31	3.5
5 (1.5)	16	1.9	17	6.5
10 (3.0)	5.5	5.5	6.3	16.9
15 (4.5)	2.1	14.3	2.9	37.9
20 (6.0)	1.3	23	2.1	52.4

Room data:

Room 24 ft × 28 ft (7.3 m × 8.5 m); 70% ceiling reflectance

Window on 28-ft (8.5-m) wall—one side only; 20% floor reflectance

Window area = 20% of floor area

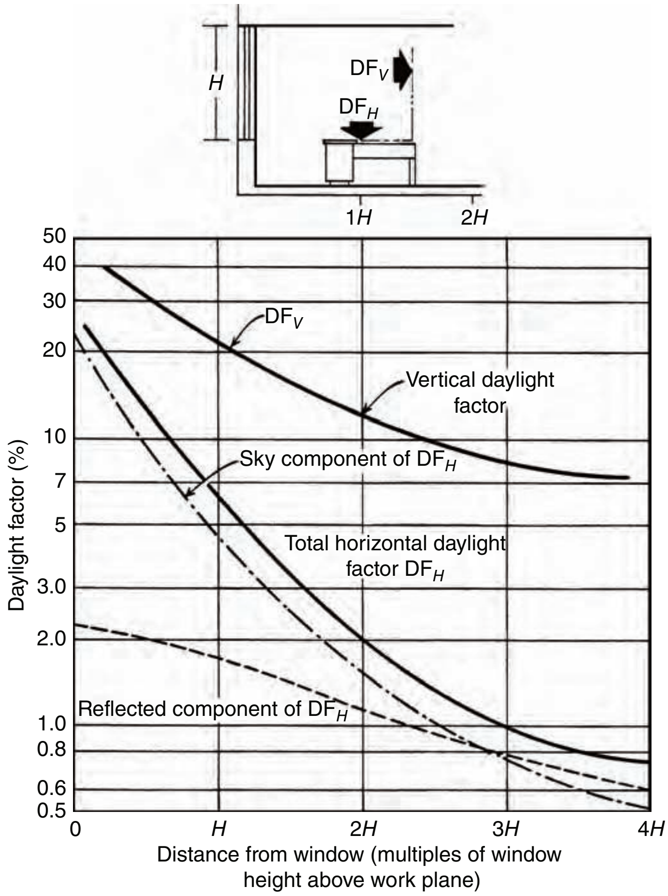


Fig. 8.29 *Typical daylight factor curves for horizontal (DF_H) and vertical (DF_V) illuminance for a room with large windows on one side only. Note that the SC represents almost the entire DF near the window, but its proportion reduces at greater depths. There, interreflected light constitutes 50% of the available daylight.*

to LEED 2009, the LEED criteria specified that a daylight factor of 2% was required in 75% of the space occupied for critical visual tasks. LEED's daylighting criteria have subsequently become more complex. As an example, we use the daylight factor method and consider two cities in the United States that have overcast skies for appreciable portions of the year—Columbus, Ohio (40°N latitude), and Seattle, Washington (48°N latitude). Table 8.4 compares illuminance values calculated by the DF method with those recommended by IESNA and the Chartered Institution of Building Services Engineers (CIBSE). For most of the year (with the exception of winter), daylight provides all the light necessary for the tasks in Table 8.3. In this case, where the available exterior daylight is as low as 5000 to 7000 lux (465 to 650 fc), supplemental electric lighting would be required for all interior areas beyond H feet (that is, one window height from the window—see Fig. 8.29).

In addition to the recommendations in Table 8.3, the ratio between the minimum and

TABLE 8.3 Recommended Daylight Factors

Task	DF[a]
Ordinary seeing tasks, such as reading, filing, and easy office work	1.5–2.5%
Moderately difficult tasks, such as prolonged reading, stenographic work, normal machine tool work	2.5–4.0%
Difficult, prolonged tasks, such as drafting, proofreading poor copy, fine machine work, and fine inspection	4.0–8.0%

Source: Millet and Bedrick (1980).

[a]Use the smaller DF values for southern latitudes with plentiful winter daylight.

average daylight factor in a space, which relates to contrast ratios, should be no less than 30%:

$$\frac{Df_{min}}{DF_{avg}} \geq 0.3$$

The minimum daylight factor in any portion of a space should not drop below 0.5%, which is sufficient for circulation.

8.11 GUIDELINES FOR PRELIMINARY DAYLIGHTING DESIGN

Guidelines provide the designer with a variety of broadly based rules useful during the conceptual and schematic stages of design. Based upon design experience and lighting research, these guidelines assume overcast sky conditions. During design development, they may be used as a starting point for performance analyses that include other parameters such as sky conditions, orientation, and wall color, using computer simulation software, physical models, and calculations.

(a) The 2.5H Guideline

This longstanding guideline in the lighting design field (Fig. 8.30) assumes that there will be sufficient work plane illuminance from a window up to a distance of 2.5 times the head height of the window above the work plane—assuming clear glazing, overcast skies, no major obstructions, and a total window width that is approximately half that of the exterior perimeter wall.

(b) The 15/30 Guideline

This preliminary design guideline assumes that a 15-ft-wide (4.6-m) zone from a window wall (Fig. 8.31) can be daylit sufficiently for office tasks. The next 15-ft (4.6-m) zone can be partially daylit and supplemented with electric lighting. Zones farther than 30 ft (9.1 m) from the window would

TABLE 8.4 Horizontal Illuminances (E_H) from Overcast Sky, at Selected Times, in Columbus, Ohio, and Seattle, Washington, Corresponding to the Recommended DF

Location	10 am Solar Altitude[a]	Available Daylight, E_H Fc (lux)[b]	DF Recommendation (%)[c]	Illuminance fc (lux) Calculation From DF	Illuminance fc (lux)[d] Recommendation
Columbus 40°N latitude	June 21 60°	2100 (22,500)	1.5–2.5	31–52 (338–563)	28–47 (300–500)
			2.5–4	52–84 (563–900)	47–70 (500–750)
			4–8	84–167 (900–1800)	70–93 (750–1000)
	Mar./Sept. 21 41°	1400 (15,500)	1.5–2.5	21–35 (225–375)	28–47 (300–500)
			2.5–4	35–56 (375–600)	47–70 (500–750)
			4–8	56–112 (600–1200)	70–93 (750–1000)
	Dec. 21 21°	700 (7500)	1.5–2.5	11–18 (113–188)	28–47 (300–500)
			2.5–4	18–28 (188–300)	47–70 (500–750)
			4–8	28–56 (300–600)	70–93 (750–1000)
Seattle 48°N latitude	June 21 56°	1950 (21,000)	1.5–2.5	29–49 (315–525)	28–47 (300–500)
			2.5–4	49–78 (525–840)	47–70 (500–750)
			4–8	78–156 (840–1680)	70–93 (750–1000)
	Mar./Sept. 21 36°	1220 (13,000)	1.5–2.5	18–30 (195–325)	28–47 (300–500)
			2.5–4	30–48 (325–520)	47–70 (500–750)
			4–8	48–97 (520–1040)	70–93 (750–1000)
	Dec. 21 14°	500 (5400)	1.5–2.5	8–13 (81–135)	28–47 (300–500)
			2.5–4	13–20 (135–216)	47–70 (500–750)
			4–8	20–49 (216–532)	70–93 (750–1000)

[a]From Appendix D.1

[b]From Fig. 8.23

[c]From Table 8.3

[d]From former CIBSE and IESNA recommendations retained here for this example: *CIBSE Code for Interior Lighting* (1994). Reference 25: CIBSE Lighting Guide LG3: Areas for Visual Display Terminals; *Code for Lighting* (2006); *IESNA Lighting Handbook*, 9th ed. (2000).

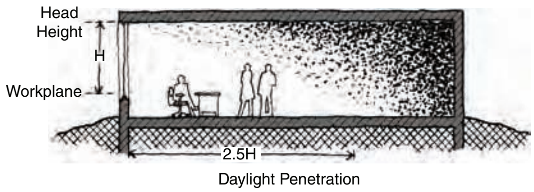


Fig. 8.30 *Section shows the 2.5H guideline, which assumes that sufficient daylight for the desk plane will be delivered at a depth 2.5 times the height of the window above the desk plane. (Drawing by Jonathan Meendering, Ayush Vaidya; © Walter Grondzik; all rights reserved.)*

receive very little daylight. In schematic design, these areas might ideally be allocated to circulation.

(c) The Sidelighting and Toplighting Daylight Factor Guideline

The size of windows, clerestories, or skylights may be estimated by using the simple formulas in Table 8.5, Parts A and B, which provide target daylight factor values. These design guidelines consider two factors: the height of the window in the wall and the window or skylight area compared to the floor area for each daylit space.

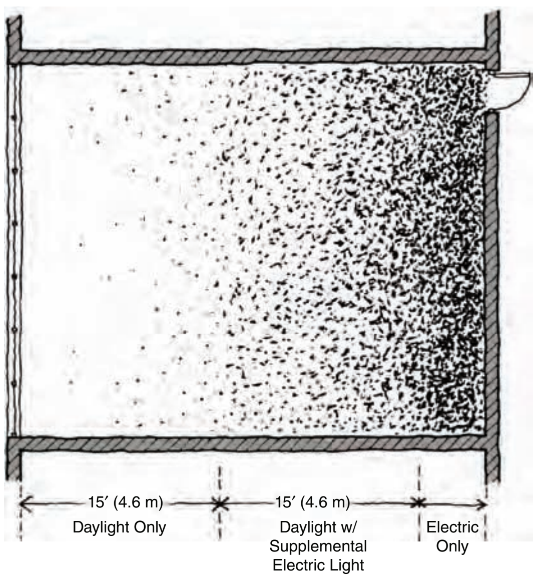


Fig. 8.31 *Plan shows the 15/30 guideline, which assumes that sufficient daylight will be delivered to the desk plane at a 15-ft (4.6-m) distance from the window wall. The 15- to 30-ft (4.6- to 9.1-m) daylight zone will need supplementary electric lighting, and the zone beyond 30 ft (9.1 m) will receive virtually no daylight. (Drawing by Jonathan Meendering, Ayush Vaidya; © Walter Grondzik; all rights reserved.)*

Table 8.5, Part C, shows design guidelines for buildings with an atrium that provides daylighting to surrounding offices. Because the lowest daylight factor will occur in offices on the lowest floor (deepest within the atrium), the designer might find the required atrium *aspect ratio* first for the lowest floor and then size the atrium on that basis. The atrium aspect ratio equals [(length × width)/height^2]. This design approach would provide a higher daylight factor in all the offices higher in the atrium. For a detailed discussion of the relationship of atrium size, rentable office floor area, and latitude, see DeKay (1992).

8.12 DESIGN ANALYSIS METHODS

Because of the variability of daylight, the designer may provide a balance of illumination to save electric energy and reduce utility costs while addressing issues of glare, direct sunlight, and heat gain. The art and science of daylighting is largely about understanding how to control the admission of daylight into buildings.

In the following sections, several interior daylighting analysis methods are described. The manual methods range from hand calculations that address only minimum, maximum, and average conditions to physical scale models where surfaces and apertures are easily changed. The manual and graphic calculation methods are inexpensive but limited to simple spatial geometries. Computer simulation programs can produce detailed and realistic presentations in three-dimensional graphical form. Software is widely available, but its use is dependent upon cost and training, and the user must understand daylighting concepts and principles in order to interpret the results and to overcome the limitations of simulation. Physical models still offer the designer an economical, realistic, and accurate alternative. Additionally, the intuitive understanding provided by scale models may increase the client's understanding of lighting phenomena.

(a) CIE Method

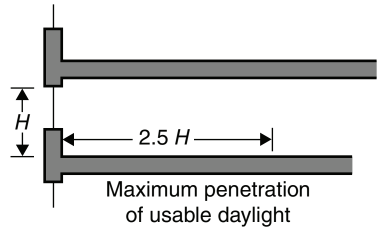
This method resulted from a search for a simple, rapid, straightforward, and reasonably accurate daylighting calculation method that would yield reliable results without the time-consuming constructions and calculations necessitated by other manual

TABLE 8.5 Daylight Factor Design Estimates for Overcast Sky Conditions

PART A. **SIDELIGHTING**[a, b]

$$DF_{av} = 0.2\left(\frac{\text{window area}}{\text{floor area}}\right)$$

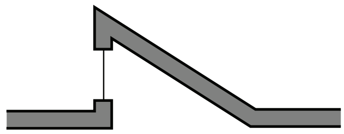
$$DF_{min} = 0.1\left(\frac{\text{window area}}{\text{floor area}}\right)$$



PART B. **TOPLIGHTING**[c]

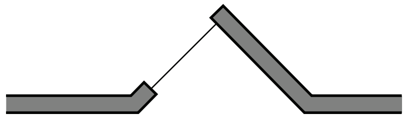
Vertical monitors:

$$DF_{av} = 0.2\left(\frac{\text{skylight glazing area}}{\text{floor area}}\right)$$



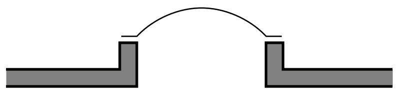
North-facing sawtooth:

$$DF_{av} = 0.33\left(\frac{\text{skylight glazing area}}{\text{floor area}}\right)$$

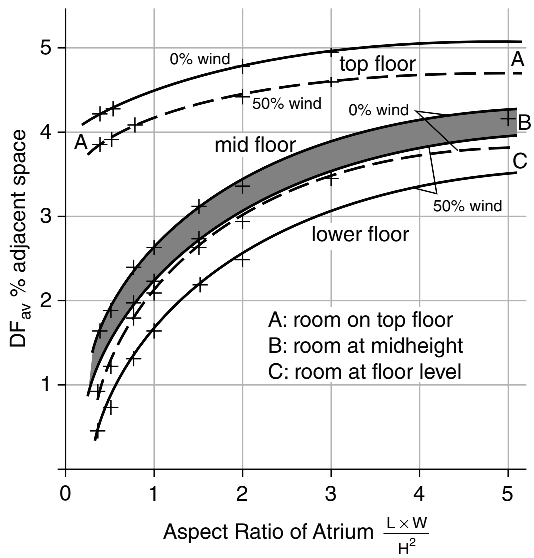


Horizontal skylights:

$$DF_{av} = 0.5\left(\frac{\text{skylight glazing area}}{\text{floor area}}\right)$$



PART C. **BUILDINGS WITH ATRIUM**[d]



Source: Parts A and B: Millet and Bedrick (1980). Part C: Brown and DeKay (2000).

[a]Assumes windows in one wall of a room with relatively light-colored surfaces.

[b]Window height/room depth relationships based on the works of R. G. Hopkinson (1966) and others at the British Research Station.

[c]Assumes an even distribution of such skylights in the roof so that an even distribution of light results in the room below: thus, only average DF, no minimum, is listed.

[d]Based on model tests of a square atrium with white walls open to the sky. "No windows" average atrium wall reflectance = 70%. "50% windows" average atrium wall reflectance = 40%. DF values are for an office of 9 m × 9 m × 3 m (30 ft × 30 ft × 10 ft). The window opening to the atrium is 1.5 m high × 9 m long (5 ft high × 30 ft long), and the sill height is 0.85 m (2.8 ft).

methods. After a study of considerable length and intensity, the CIE adopted and adapted a system developed in Australia by Dresler (Dresler, 1963). The current CIE method was published in *Daylight*, 1970.

This system is based upon the daylight factor described previously as applied to the *standard overcast CIE sky*. Dresler developed a set of more than 100 curves covering rooms of varying proportions and fenestration. A typical curve is shown in Fig. 8.32. The curves relate minimum daylight factor (at a point 2 ft [0.6 m] from the wall opposite a window) to the maximum permissible room depth, for given reflectances and a standard window design, thus establishing the room's proportions. Depth, or width, is the dimension at right angles to the window wall.

The curves imply that the number of design variables is so large and daylight itself is so variable that a simple routine method can be based only on minimal conditions for a given (selected) daylight duration. Therefore, the diagrams give the *lowest* level of daylight that can reliably be expected for a given percentage (percentile) of normal working hours in sidelighted rooms and the *average* level in toplighted spaces.

Advantages of the system are:

1. It allows consideration of obstructions, exterior reflections, and interior reflections.
2. It is applicable to a very wide range of side and top fenestration designs.
3. Establishment of required room proportions is architecturally more useful than solving for specific dimensions.

Limitations of the system are:

1. It is inapplicable to clear-sky and direct-sun conditions.
2. It is inapplicable to other than rectangular rooms.
3. It is unusable with sunshading devices or high-reflectance ground.
4. Results give points of minimum, twice minimum, and four times minimum daylight only. Other points must be interpolated or extrapolated.
5. Window proportions and position in a wall are fixed.

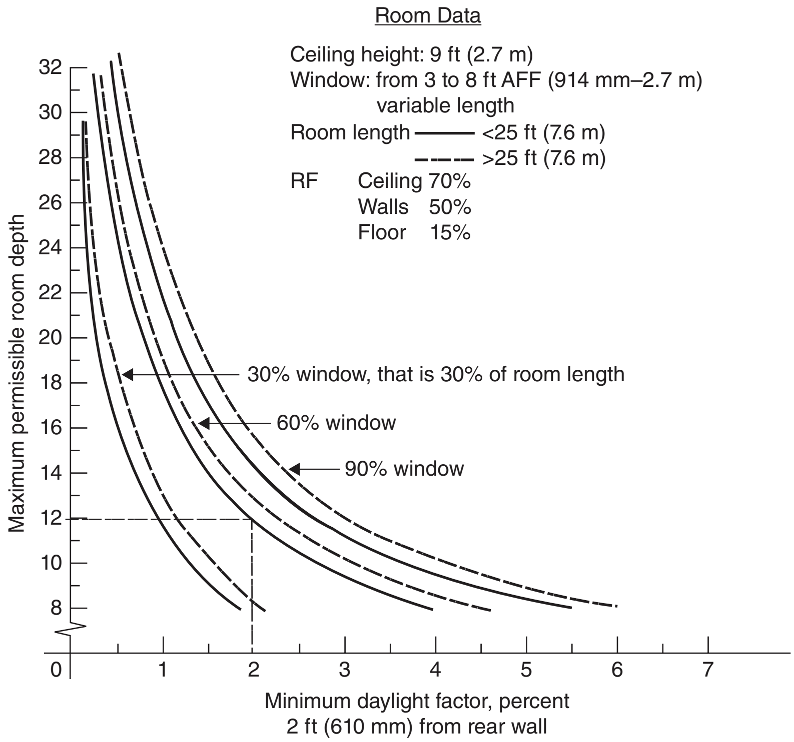


Fig. 8.32 *Maximum room depth that will maintain a minimum daylight factor is proportional to window size. Thus, for a room less than 25 ft (7.6 m) long with a 5-ft- (1.5-m)-high window for 60% of the room's length, the depth cannot exceed 12 ft (3.7 m) if 2% DF is to be maintained at a point 2 ft (61 cm) from the rear wall. (From Daylight Design Diagrams, 1963.)*

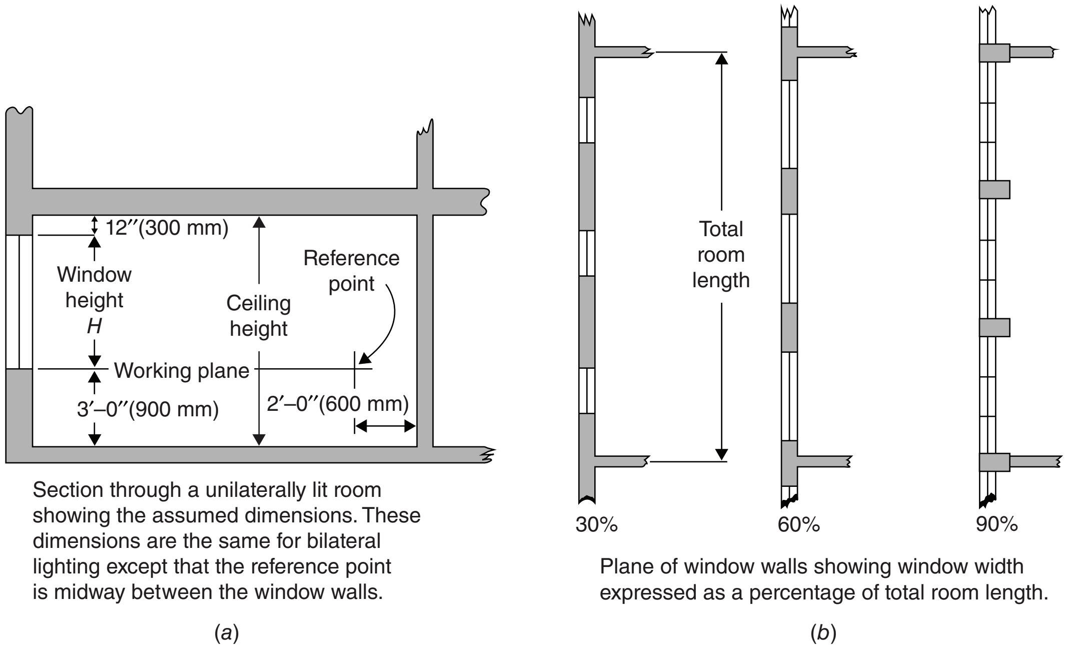


Fig. 8.33 *Sketches indicating the parameters of the CIE calculation system. (a) A vertical section through a room with dimensional data relevant to this system. Note that the sill height has been selected to coincide with a working plane at 900 mm (3 ft). The height of the working plane usually varies between 760 and 910 mm (30 and 36 in), the former being more common in North America, the latter in Europe. A lower sill contributes only ground-reflected light at the working plane. Where the window sill is significantly above the working plane (i.e., short windows high on a wall), this analysis system is inapplicable. (b) Calculation size (length) of windows with respect to overall room length. (From* Daylight, International Recommendations for the Calculation of Natural Daylight*, 1970, Commission Internationale de l'Eclairage; reproduced with permission.)*

Overall, the system accomplishes what it intended. The limitations listed are inherent in any quick, simplified daylight calculation technique.

The CIE system is usable in two modes:

1. Given complete architectural dimensional data, find interior illuminance.
2. Given incomplete architectural dimensional data and required interior illuminance, find maximum room depth and/or other room proportions that satisfy the illuminance requirement.

Mode 1 is simpler because it leads directly to an answer. For this reason, the designer should set the room length (window wall dimension) and percentage of fenestration of the window wall, leaving the room depth (perpendicular to window wall) as a variable. Alternatively, room length and depth may be set, with percentage of fenestration as the variable. Ceiling height is usually fixed. See Fig. 8.33 for sketches showing room parameters.

EXAMPLE 8.1 An example of the CIE method in Mode 1 uses a classroom in a single-story Seattle elementary school, 25 ft (7.6 m) long, 18 ft (5.5 m) deep, and with a 9.5-ft (3-m) ceiling. It receives daylight unilaterally from windows totaling 18 ft (5.5 m) in length (see the room sketch in Fig. 8.34). Window glazing is wired glass having a transmittance of 80%. The school is situated in a dense residential area. Determine the portion of the year during which tasks requiring a minimum illuminance of 14 fc (150 lux) can be carried out by daylight throughout the room. Also, determine what illuminance levels can be maintained for 85% of daylight hours and at what distances from the window. (Note that 14 fc [150 lux] corresponds to a DF of 2% applied to an E_H of 70 fc [7500 lux].)

Calculation. The latitude of Seattle is 47.6°N. The design condition for Seattle is solid overcast sky for 85% of the hours between 9:00 A.M. and

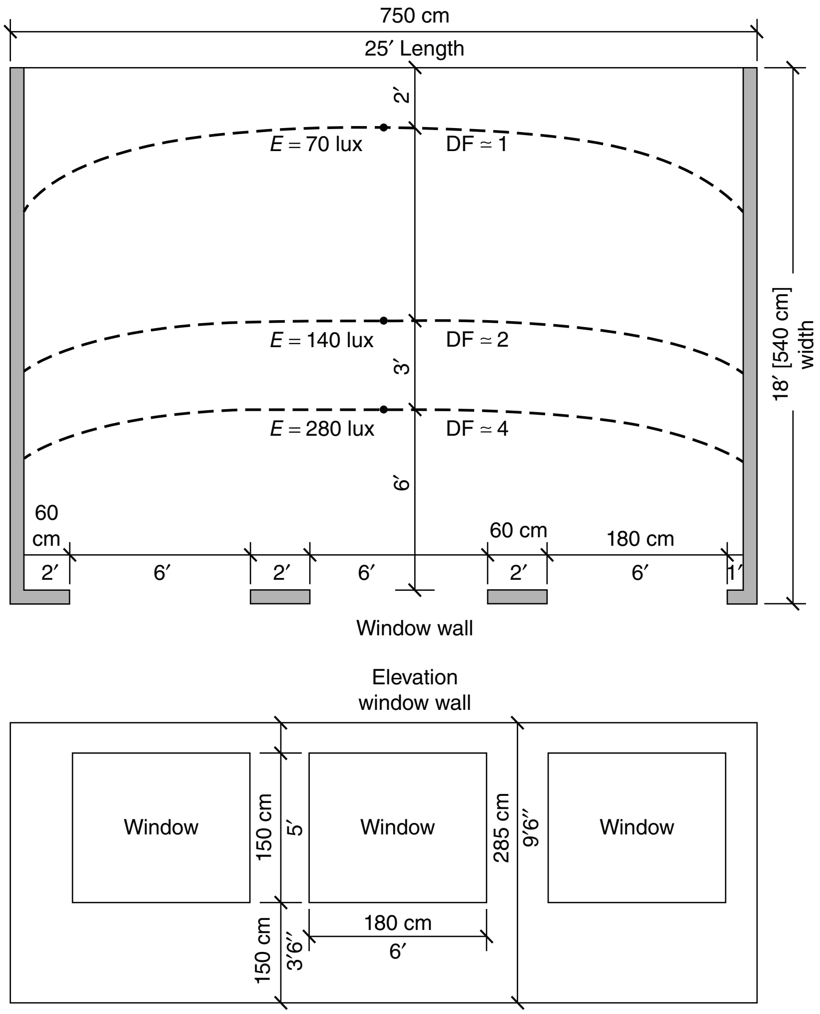


Fig. 8.34 *Plan and window wall elevation of the Seattle classroom calculation example using the CIE method. The three daylight contours are estimated based upon the calculated center point. They represent the levels maintained for 85% of daylight hours. Levels twice as high are maintained for 60% of the daylight hours.*

5:00 P.M. From Fig. 8.35, the minimum unobstructed horizontal illuminance E_H during these hours is 67 fc (7200 lux).

STEP 1. Determine the room depth in terms of window height. Window height *H* is 5 ft (1.5 m) (see Fig. 8.34). In plan, the room depth is expressed as multiples of window height above sill level:

$$\frac{\text{18-ft depth}}{\text{5-ft window height}} = 3.6H$$

STEP 2. Determine window coverage. This variable is expressed as a percentage of the total room length based upon the width of the glazing used in the room. It is assumed that the window head is 12 in. (305 mm) below the ceiling. This distance was selected as the representation of best practice "without being unduly optimistic."

$$\frac{3 \times 6\ \text{ft}}{25\ \text{ft}} = 72\%$$

STEP 3. Determine the design daylight factor and the service daylight factor. The design daylight factor is calculated at a point 2 ft (0.6 m) from the wall opposite the window—on the window centerline. This represents the minimum daylight factor that will occur in a room of a given depth (lower values that will occur closer to the wall and/or off the

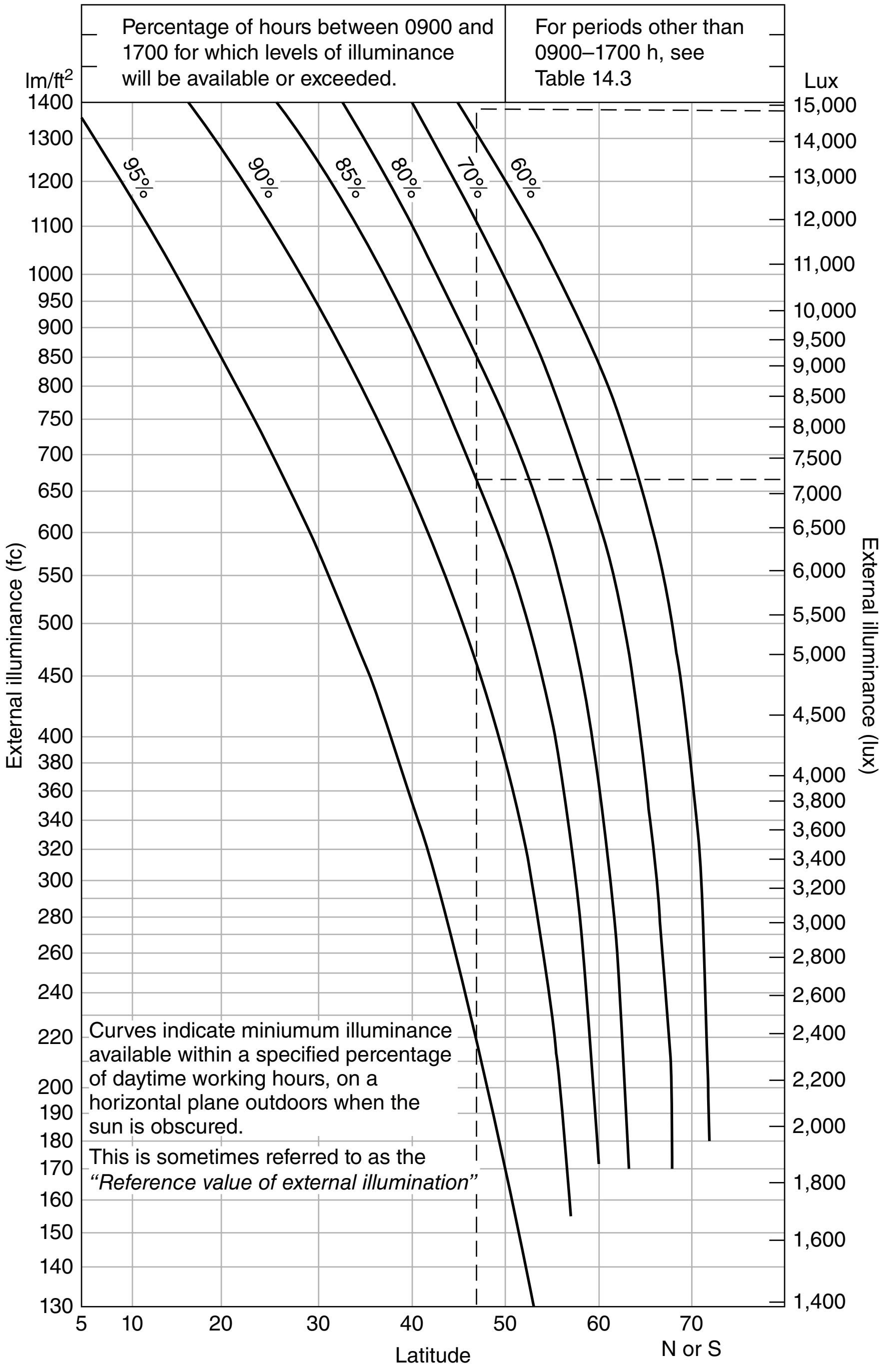


Fig. 8.35 *Minimum maintained external illuminance as a function of latitude for a given percentage of the normal working day. (From* Daylight: International Recommendations for the Calculation of Natural Daylight*, 1970, Commission Internationale de l'Eclairage; reproduced with permission.)*

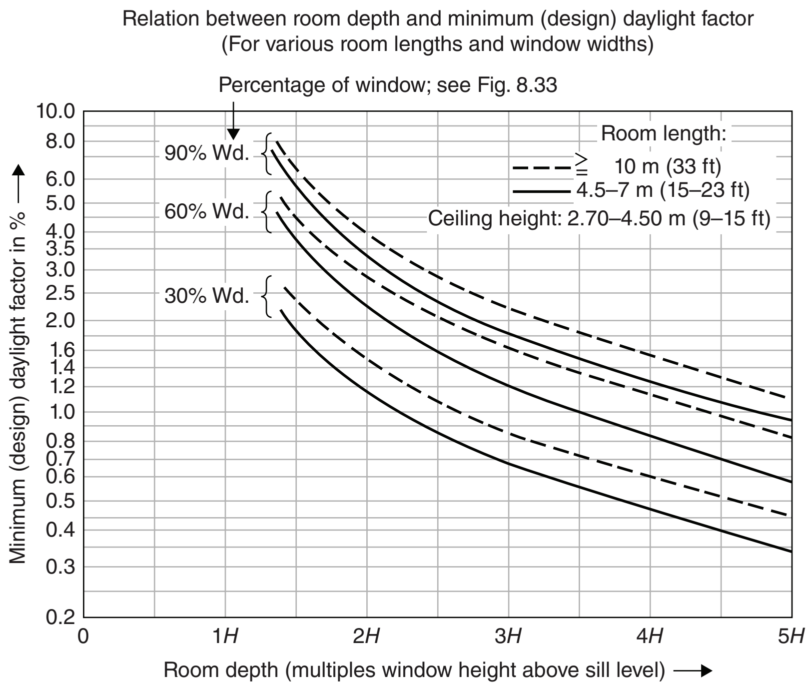


Fig. 8.36 *Basic design diagram that relates minimum daylight factor to room depth. Inasmuch as room depth is expressed in terms of window height, the curves effectively relate minimum daylight factor (2 ft [610 mm] from the back wall) to room proportion. (From* Daylight: International Recommendations for the Calculation of Natural Daylight*, 1970, Commission Internationale de l'Eclairage; reproduced with permission.)*

centerline being discounted). From Fig. 8.36, for a room length of 25 ft (7.6 m), ceiling height 9.5 ft (2.9 m), window coverage 72%:

design daylight factor at 3.6 H = 1.3

The service daylight factor takes into account correction factors such as glazing transmission and dirt accumulation. The service daylight factor is a product of the design daylight factor and correction factors.

$$DF_{service} = DF_{design} \times \text{correction factors}$$

Correction factors from Table 8.6 and Fig. 8.37 are:

Glass transmission 0.95
Glass cleanliness 0.8

Therefore

$$DF_{service} = 1.3 \times 0.95 \times 0.8 \approx 1.0$$

Note that the terms "design" and "service" as used in this method have meanings that are not necessarily consistent with normal design practice. Design daylight factor typically would include the effects of building components such as glazing—and would often be described as "initial" daylight factor. Service daylight factor would often be called "maintained" daylight factor and include those effects that would reduce daylight illuminance over time (such as dirt on glazings or reductions in surface reflectances). Maintained daylight factor must equal or exceed the designer's daylight factor criterion for the system to be successful in the long run.

STEP 4. Determine the required exterior illuminance. Use the service daylight factor in Equation 8.4 to obtain required exterior illuminance.

E_H, required exterior illuminance

$$= \frac{\text{required interior illuminance}}{DF_{service}} \qquad (8.4)$$

$$E_H = \frac{150\ \text{lux min}}{1.0} \times 100 = 15{,}000\ \text{lux}$$

STEP 5. Obtain the percentage of hours between 9:00 A.M. and 5:00 P.M. during which the required illuminance is maintained. From Fig. 8.35 with the given conditions (roughly 48°N latitude, exterior

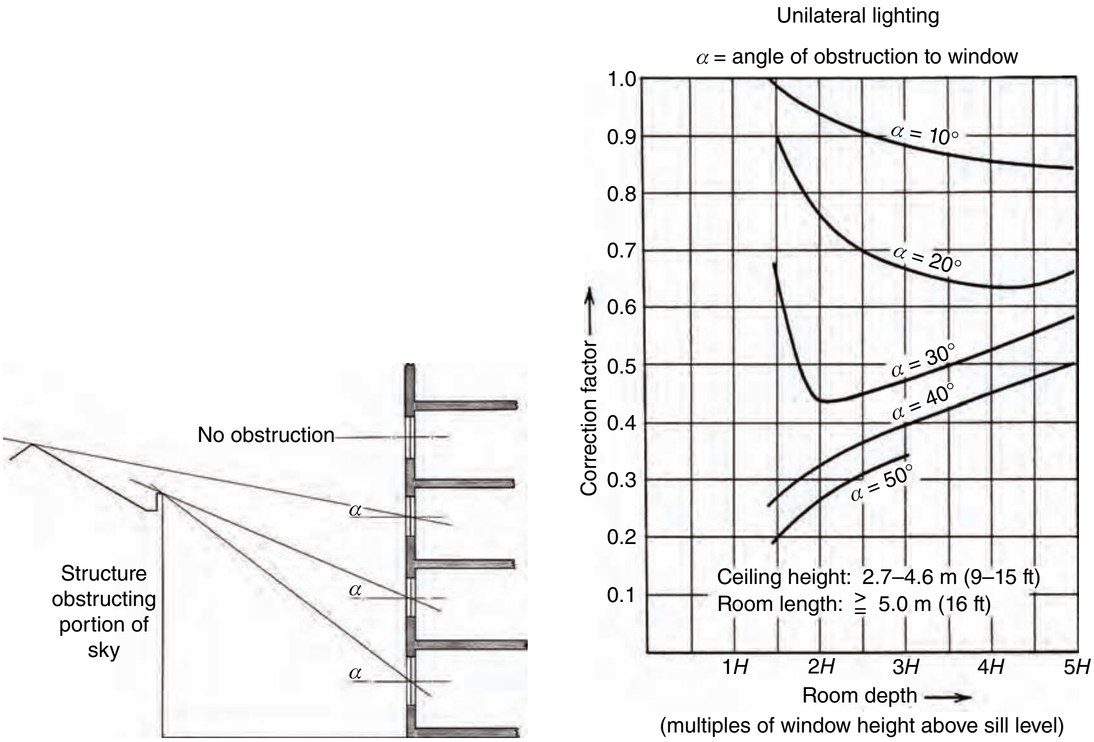
TABLE 8.6 Correction Factors to Be Used in CIE Daylight Calculations

A. CORRECTION FACTOR TO ACCOUNT FOR GLASS TRANSMITTANCE	
Diffuse Transmittance of Glass (%)	**Correction Factor**
80	0.95
70	0.80
60	0.70
50	0.60
40	0.45
30	0.35

B. CORRECTION FACTORS TO ACCOUNT FOR DIRT ACCUMULATION ON GLASS				
		Angle of Slope (Measured to the Horizontal)		
Locality	**Class of Industry**	**90–75°**	**60–45°**	**30–0°**
Country or outer-suburban area	Clean	0.9	0.85	0.8
	Dirty	0.7	0.6	0.55
Built-up residential area	Clean	0.8	0.75	0.7
	Dirty	0.6	0.5	0.4
Built-up industrial area	Clean	0.7	0.6	0.55
	Dirty	0.5	0.35	0.25

C. PERCENTAGES TO USE WHEN FIGURE 8.35 CURVES ARE APPLIED TO PERIODS OTHER THAN 09.00–17.00						
Curve in Figure 8.35	**95%**	**90%**	**85%**	**80%**	**70%**	**60%**
Alternative period			Percentage of alternative period			
07.00–15.00	95	90	85	80	70	60
08.00–16.00	100	100	95	85	70	60
07.00–17.00	95	85	75	65	55	45
06.00–18.00	75	70	65	60	50	40

Source: Daylight: International Recommendations for the Calculation of Natural Daylight (CIE, 1970).



(*a*) (*b*)

Fig. 8.37 *(a) Angle of obstruction α of an external object. (b) Correlation factors to account for the influence of external obstructions on the minimum daylight factor. (From* Daylight, International Recommendations for the Calculation of Natural Daylight, *1970, Commission Internationale de l'Eclairage; reproduced with permission.)*

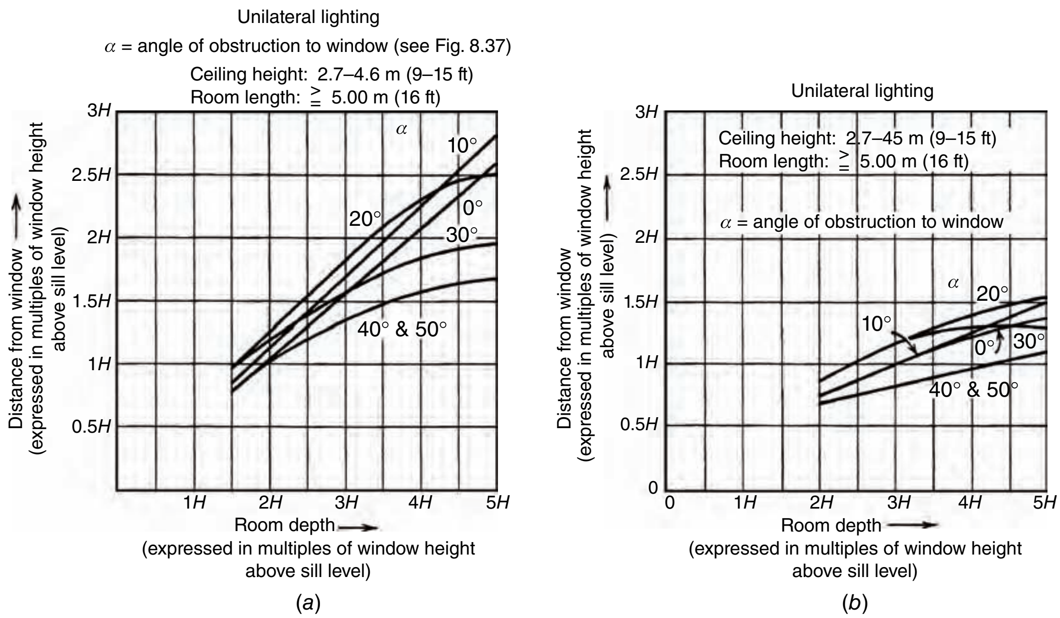


Fig. 8.38 (a) Distance from the window at which the daylight factor is twice the minimum daylight factor. (b) Distance from the window at which the daylight factor is four times the minimum daylight factor. (From Daylight: International Recommendations for the Calculation of Natural Daylight*, 1970, Commission Internationale de l'Eclairage; reproduced with permission.)*

illuminance 15,000 lux [1500 fc]), an illuminance of 150 lux (15 fc) will be maintained for less than 60% of the hours between 09:00 A.M. and 5:00 P.M. (for time periods other than this, see Table 8.6C). The level that is maintained for 85% of the hours is

$$E_{min} = 7200 \text{ lux} \times 0.01 \text{ (a DF of 1.0)} = 72 \text{ lux}$$

STEP 6. Determine the locations in the room that will receive adequate illuminance. Figure 8.38 shows the distance from the window at which the daylight factor is twice or four times the minimum. Using Fig. 8.38*a*, the room depth from Step 1 is 3.6*H*. This point intersects with the $\alpha = 0°$ angle of obstruction line at a 1.8*H* distance (1.8 × 5 ft = 9 ft [2.7 m]) from the window, resulting in a doubling of the daylight factor.

$$7200 \text{ lux} \times 0.02 \text{ (a DF of 2.0)} = 144 \text{ lux}$$

Using Fig. 8.38*b*, the room depth from Step 1 is 3.6*H*. This point intersects with the $\alpha = 0°$ angle of obstruction line at a 1.2*H* distance (1.2 × 5 ft = 6 ft [1.8 m]) from the window, resulting in a quadrupling of the daylight factor quadruples.

$$7200 \text{ lux} \times 0.04 \text{ (a DF of 4.0)} = 288 \text{ lux}$$

These calculated illuminance levels are accurate only at the centerline of the window wall. By visual estimate and extrapolation, rough contours can be drawn and are shown in Fig. 8.39 (for comparison with the graphic method discussed in the next section). For bilateral sidelighting, toplighting (skylights, sawtooth roofs, and monitor roofs), and calculations for other α angles of obstruction, additional information is found in the CIE document (CIE, 1970). ■

In summary, the CIE method is relatively simple but provides only limited data on predicted performance. In this example, its exterior illuminance data (7250 lux from Fig. 8.35) seem to agree well with a measured average value of 7200 lux for Seattle. From the rough contours shown in Fig. 8.39, an integrated daylight and electric lighting strategy should be designed for areas farther from the window wall.

(Reminder: The term *design illuminance* as used with the CIE method differs from common lighting system design usage, where *design illuminance* is used to identify the criteria (benchmark) illuminance established for a space or position; *initial illuminance* identifies the illuminance actually provided at system startup, and *maintained illuminance* is the illuminance provided after some defined time period.)

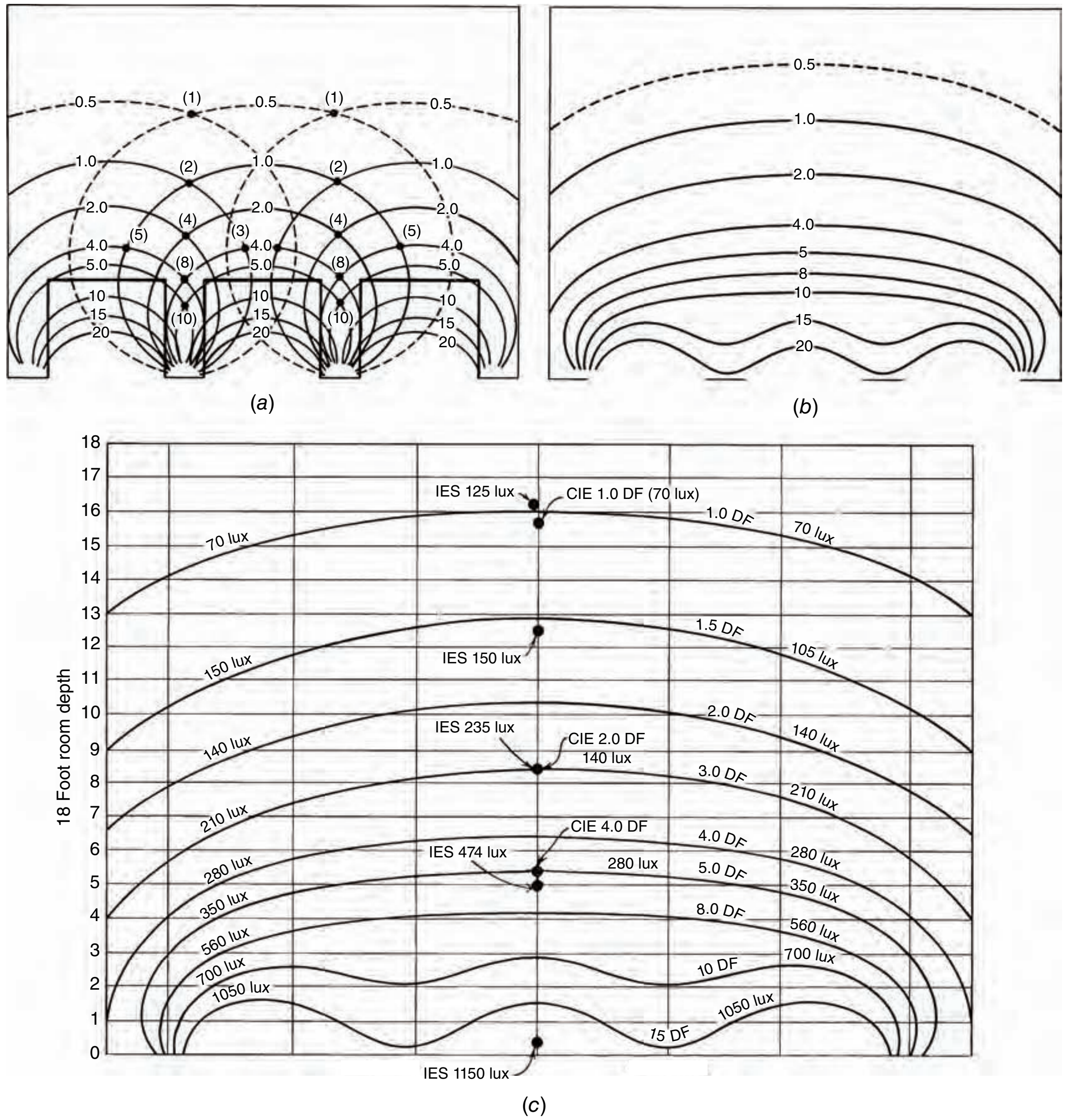


Fig. 8.39 *(a) Daylight contours for each window of Fig. 8.34 are plotted on the floor plan of the room being studied. Numbers in parentheses are combined SC values. (b) The isolux contours of (a) are combined to form new isolux contours that represent the total SC of daylight within the room. (c) The final isolux contours are calculated, including correction factors (accounting for internally reflected components of daylight plus light reduction due to glazing). The numbers represent daylight factors. Note the variance between these contours and the points calculated by the CIE method. The five design points calculated by the IESNA method are also shown. A comparison of the results on the room centerline (a location where comparison of all methods is possible), agreement is within engineering accuracy (see text discussion).*

(b) Graphic Daylighting Design Method (GDDM)

This method, which applies to overcast sky conditions and shows results as daylight factor (isolux) contours within a room (rather than individual daylight factors at specific points), was developed by Millet and Bedrick (1980). Its primary advantage over the CIE method is that its results are a family of daylight factor contours that are more useful to a lighting designer than is numerical output. The disadvantages of this method are that it is not readily applicable to clear-sky conditions, and it requires that a designer acquire a "library" of 200 or so patterns that cover most design situations. An outline of the method is presented here.

A computer simulation program (UWLIGHT) developed the daylight distribution patterns resulting from either sidelights or skylights. To generalize the system, windows are identified by height-to-width proportion (*H*/*W*), and the positions of the isolux contours on the plan are determined by the ratio of the height of the sill above the work plane to the window height. The GDDM method can account for high windows, clerestories, and other designs intended to introduce daylight deep into a space—something that the CIE method cannot do because it is restricted to a sill height *at* the work plane.

EXAMPLE 8.2 Figure 8.40 shows a typical isolux pattern for a window whose *H/W* ratio is 0.8 and whose sill is at the work plane. This particular window pattern was selected because it corresponds to the window in the previous example, Fig. 8.34, enabling graphical comparison.

Calculation. Employing the GDDM method with the dimensions of the Seattle classroom used in the last section:

STEP 1. Determine the window proportion. Referring to Fig. 8.34, the window proportion is

$$\frac{H}{W} = \frac{5}{6} = 0.83$$

STEP 2. Select the appropriate window pattern. In this case, Fig. 8.40 (selected from a library of isolux patterns developed by Millet and Bedrick) is the closest pattern to match the example. *S/H* = 0 indicates that the pattern begins at the window wall, as shown.

STEP 3. Develop an isolux pattern for each window of the space. On a plan of the room, trace the isolux pattern for each window (Fig. 8.39*a*). The patterns overlap because the windows are close together. Where contours meet, the daylight factors of the contours are added together, producing values for the new combined contours. The combined contours and their daylight factors are shown in Fig. 8.39*b*.

STEP 4. Make corrections to the isolux pattern. The value of the combined contours is corrected to account for internally reflected components of daylight plus light reduction due to glazing. The final contours are shown in Fig. 8.39*c*. Note that this diagram gives the designer a much more complete picture of the daylight contours than do the results of the CIE method. For the purpose of comparison, the three calculated daylight factors from the CIE method are shown in Fig. 8.39*c*. ■

(c) IESNA Lumen Method

IESNA developed the lumen method for calculating daylight availability (published as RP-23-89,

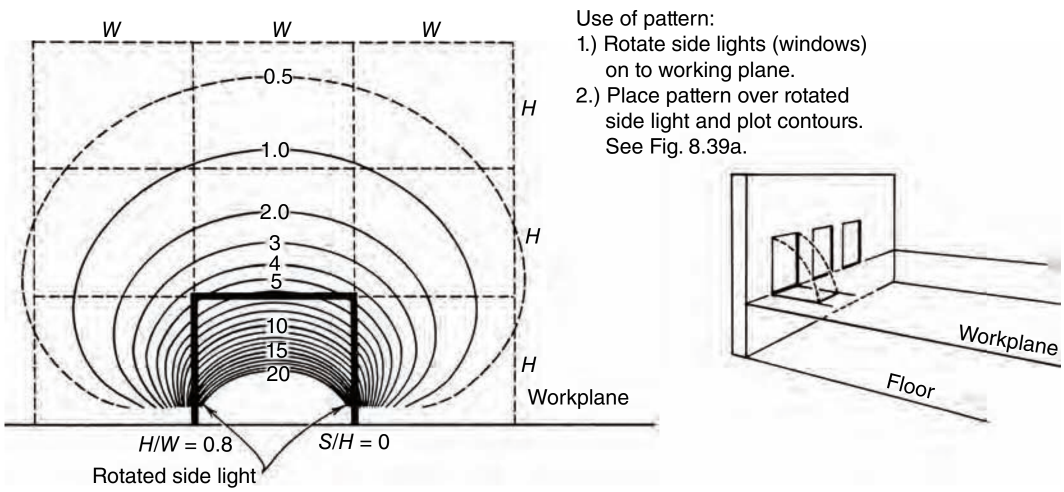


Fig. 8.40 *Typical isolux contour map for a window with a height-to-width ratio of 0.8 and a sill at the working plane elevation. Numbers represent the SC of daylight factors for an overcast sky condition. The rectangles are the window outlines rotated (projected) onto the working plane. See insert. (From Millet and Bedrick, 1980, p. 191.)*

Recommended Practice for the Lumen Method of Daylight Calculations). Although inexpensive, like many manual methods it is limited in application—in this case, to rectilinear spaces with flat ceilings. A trade-off between usability, learning curve, and cost, however, is often made when selecting a design method.

The calculation procedure for sidelighting is discussed in this section, as this is a more frequently encountered strategy than toplighting. The method, as fully described in RP-23-89, consists of four detailed steps. In the discussion that follows, the same notation and terms found in RP-23-89 are used *except* for *bearing angle*, which is referred to in the IESNA procedure as *solar window azimuth*. The term *bearing angle* is commonly used in international sources.

Characteristics of the Method. The IESNA method is probably the most flexible manual technique available. It has the following major characteristics for sidelighting:

1. It takes into account reflected light from the ground and adjacent structures, as well as the reduction in sky light due to such structures.
2. It cannot accommodate direct sunlight, but conversely, it readily accommodates the shading devices normally used to block direct insolation.
3. Provision is made for various types of glazing, as well as common window controls such as horizontal and vertical blinds.
4. The principles of the zonal cavity calculation approach for interior lighting are applied. The window height determines the cavities (i.e., the floor cavity extends to the windowsill height, and the ceiling cavity from the top of the window to the ceiling). The room cavity is therefore the window height.
5. The work plane is always at the sill height of the window. Where this is decidedly not the case (a difference of up to 1 ft is usually negligible), such as when a clerestory or a floor-to-ceiling window is used, work plane illuminance can be calculated by superposition. For instance, with a clerestory, subtract a work-plane-to-clerestory sill height window from a work-plane-to-top-of-clerestory window to obtain the desired result. A degree of inaccuracy is unavoidable in the calculation when the work plane is *above* the sill.
6. Cavity reflectances are fixed (Fig. 8.41) at 70%-50%-30% for ceiling, room, and floor cavities, respectively.
7. The system calculates only five points in a room on the window centerline. As noted with reference to the three points calculated by the CIE

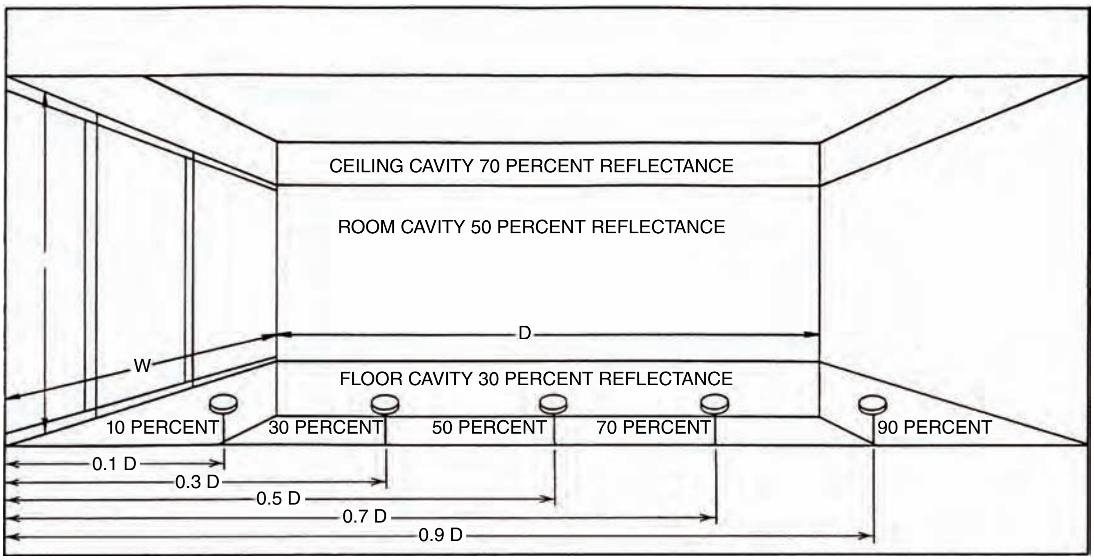


Fig. 8.41 *Standard conditions in a room for daylighting calculations: sidelighting. (IESNA, Recommended Practice for the Lumen Method of Daylight Calculations, RP-23-89.)*

method, this is not normally sufficient to give a picture of the interior daylight distribution.

8. The method is usable in only one mode—that is, given location and full dimensional data, daylighting can be calculated. It cannot readily be used to determine desirable room proportions, given the other data, as can the CIE method.

EXAMPLE 8.3 To again use the Seattle classroom as an example, here are the conditions of the problem:

Location: Seattle, Washington

Latitude: 47.6°N

Room: 25 ft (7.6 m) long, 18 ft (5.5 m) deep, with a 9.5-ft (3-m) ceiling

Window: height 5 ft (1.5 m) above a 30-in. (760-mm) working plane; total length, 18 ft (5.5 m)

Transmittance: 85%; net glass area 92%

Ground reflectance: Not previously specified. Assume an extensive area of mixed grass, asphalt, and concrete walkways, with an average overall reflectance of 20% (see Table 8.10). For a more accurate calculation of reflectance, see the method described in the *IES Recommended Practice for the Calculation of Daylight Availability* (IESNA, 1994).

Calculation. Illuminance E_i will be found at the five points shown in Fig. 8.41 for a spring day and a winter day at 10:00 A.M. and 2:00 P.M. Assume that the sky is overcast so that a direct comparison with other methods can be made. Reflectances are assumed to be 70% for the ceiling, 50% for the wall, and 30% for the floor to correspond to the IESNA method standard conditions.

STEP 1. Determine the vertical and horizontal illuminance on the exterior of the window.

Using the solar altitude for the spring and winter day (Table D.1, solar data), the vertical and horizontal illuminances can be found from Fig. 8.23. Calculate E_{xhk}, the half-sky illuminance (a vertical window sees only half of the sky). The results are compiled in Table 8.7.

Vertical illuminance from the ground is

$$E_{xvg} = RF_g \times \frac{E_{xHk}}{2} \tag{8.5}$$

$$\text{Dec. 21: } E_{xvg} = RF_g \times \frac{E_{xHk}}{2} = 0.2\ (5380) = 1076 \text{ lux}$$

$$\text{Mar. 21: } E_{xvg} = 0.2\,(13{,}340) = 2670 \text{ lux}$$

STEP 2. Determine net transmittance of the window. A number of factors affect the transmittance of light through glazing. The net transmittance is the product of the glazing transmittance (Table 8.8) and a light loss factor (Table 8.9), which represents the cleanliness of the window. The net transmittance should also account for the net glazing area (i.e., gross window area less mullions, glazing bars, and so on) and any other factor (such as insect screens) that would reduce actual transmittance.

Glass transmittance is 85% (Table 8.8), light loss factor is 0.9 (Table 8.9), and the net glass area is given as 92%. The net transmittance (τ) of the window is a product of these factors:

$$\tau = (0.85)(0.9)(0.92) = 0.70$$

STEP 3. Select coefficients of utilization for the five calculation locations (10%, 30%, 50%, 70%, and 90%) from Tables C.21–C.26 on the basis of room dimensions and the portion of the sky seen by the window. The SC seen by the window is determined by the ratio of vertical to horizontal illuminance at the window.

SC E_{xvk}/E_{xhk}: (from Table 8.7)

Dec. 21: 2150/2690 = 0.8
Mar. 21: 5380/6670 = 0.8

The E_{xvk}/E_{xhk} = 0.8 value corresponds most closely to the E_{xvk}/E_{xhk} = 0.75 value of Table C.21. Use the following values to find the coefficients of utilization, CU_k:

$$\frac{\text{room depth}}{\text{window height}} = 18/5 = 3.6$$

use 4.0 (first column variable)

TABLE 8.7 Vertical and Horizontal Illuminance Values for Spring and Winter, Seattle, Washington

Solar Altitude (Appendix D.1)	Vertical Window Illuminance, E_{xvk} (Fig. 8.23)	Horizontal Illuminance from Full Sky, E_{xHk} (Fig. 8.23)	Horizontal Illuminance from Half Sky, E_{xhk}
Dec. 21: 14°	200 fc (2150 lux)	500 fc (5380 lux)	250 fc (2690 lux)
Mar. 21: 36°	500 fc (5380 lux)	1,240 fc (13,340 lux)	620 fc (6670 lux)

TABLE 8.8 Transmittance Data for Glass and Plastic Materials

Material	Approximate Transmittance (%)
Polished plate/float glass	80–90
Sheet glass	85–91
Heat-absorbing plate glass	70–80
Heat-absorbing sheet glass	70–85
Tinted polished plate	40–50
Figure glass	70–90
Corrugated glass	80–85
Glass block	60–80
Clear plastic sheet	80–92
Tinted plastic sheet	9–42
Colorless patterned plastic	80–90
White translucent plastic	10–80
Glass-fiber-reinforced plastic	5–80
Double glazed—two lights clear glass	77
Tinted plus clear	37–45
Reflective glass[a]	5–60

Source: IES Recommended Practice for the Lumen Method of Daylight Calculations, RP-23-1989; reprinted with permission.

[a]Includes single glass, double-glazed units, and laminated assemblies. Consult manufacturer's material for specific values.

TABLE 8.9 Typical Light Loss Factors for Daylighting Design

	Light Loss Factor Glazing Position		
Location	Vertical	Sloped	Horizontal
Clean areas	0.9	0.8	0.7
Industrial areas	0.8	0.7	0.6
Very dirty areas	0.7	0.6	0.5

Source: IES Recommended Practice for the Lumen Method of Daylight Calculations, RP-23-1989; reprinted with permission.

$$\frac{\text{window length}}{\text{window height}} = 18/5 = 3.6$$

use 4.0 (first row variable)

The ground component vertical illuminance (E_{xvg}) is the product of the ground reflectance (Table 8.10) and half of the horizontal illuminance (Equation 8.5). The sky and ground component values are compiled in Table 8.11 for each of the five reference locations (from C.21 and C.26).

STEP 4. Calculate the illuminances for each of the five reference locations. (Table 8.12 tabulates the illuminance values from this calculation.) The basic equation for each location is

$$E_i = \tau(E_{xvk} \times CU_k + E_{xvg} \times CU_g) \qquad (8.6)$$

where

E_i = interior illuminance at a specific reference point
τ = net transmittance of the window
E_{xvk} = exterior vertical illuminance at the window from half of the sky (an unobstructed vertical window sees only half of the sky)
E_{xvg} = exterior vertical illuminance at the window from the ground
CU_k = coefficient of utilization for sky light
CU_g = coefficient of utilization for ground light

To compare the lumen method results with the CIE and GDDM methods, the values calculated

TABLE 8.10 Reflectances of Building Materials and Outside Surfaces

Material	Reflectance (%)
Aluminum	85
Asphalt (free from dirt)	7
Bluestone, sandstone	18
Brick	
Light buff	48
Dark buff	40
Dark red glazed	30
Red	15
Yellow ochre	25
White	75
Cement	27
Chromium	65
Concrete	55
Copper	40
Earth (moist cultivated)	7
Granolite pavement	17
Glass	
Clear	7
Reflective	20–30
Tinted	7
Grass (dark green)	6
Gravel	13
Granite	40
Marble (white)	45
Macadam	18
Marble	45
Paint (white)	
New	75
Old	55
Plaster	
Smooth	80
Rough	40
Stippled	40
Slate (dark clay)	8
Snow	
New	74
Old	64
Vegetation (mean)	25

Source: Values compiled from Lam (1986), Stein and Reynolds (1992), and the Lighting Design Lab (© 2005; used with permission).

TABLE 8.11 Coefficients of Utilization for Sky and Ground Components for Five Interior Locations

Location	CU_k (Sky)	CU_g (Ground)
10	0.673	0.183
30	0.235	0.159
50	0.104	0.103
70	0.065	0.071
90	0.053	0.060

TABLE 8.12 Illuminance Values for Winter and Spring in Seattle, Washington, at Five Reference Locations

Location	E_i Dec. 21, lux (fc)	E_i Mar. 21, lux (fc)
10	1151 (107)	2877 (267)
30	474 (44)	1182 (110)
50	234 (22)	585 (54)
70	151 (14)	378 (35)
90	125 (12)	312 (29)

for December 21 are plotted on the room plan of Fig. 8.39. The December values are minimum values and correspond most closely to the 85th percentile figures of the CIE and GDDM methods. The agreement is excellent for the half of the room nearest the window. For the deeper half, where there is significant ground contribution, the IESNA method yields higher illuminances because it considers the re-reflected ground light contribution. Over all, the agreement among the three methods is excellent. The figures for March 21 correspond most closely to the 50th to 60th percentile of Fig. 8.35, that is, somewhat more than double the minimum figures—and here again the agreement is good.

To demonstrate the use of the IESNA method for clear-sky conditions, we can work through a brief example where five IESNA point illuminances are calculated for the same Seattle classroom, on June 21 at 10:00 A.M. for clear-sky conditions. Assume that the window faces southwest (azimuth angle = 45° west of south).

Solar azimuth at 10:00 A.M. on June 21 at 48°N latitude is 56° (Table D.1). The bearing angle is therefore 45° + 56° or 101° (i.e., no direct sunlight enters the window, which is a necessary condition of the IESNA clear-sky method). Solar altitude is 55°.

Calculation

STEP 1. Determine the horizontal illuminance (refer to Fig. 8.24):

Sun only:	80,000 lux (7432 fc)
Sky only:	18,000 lux (1672 fc) full sky
	9000 lux (836 fc) half sky (E_{xhk})

TABLE 8.13 Illuminance Values for Clear-Sky Conditions on June 21 at Five Reference Locations

Location	E_i June 21, lux (fc)
10	4674 (434)
30	2225 (207)
50	1188 (110)
70	784 (73)
90	652 (61)

Determine the vertical illuminance (refer to Fig. 8.26b):

At a solar altitude of 55° and a bearing angle of 101°, the E_{xvk} = 700 fc (7500 lux).

From Equation 8.5, vertical illuminance on the exterior of the window resulting from ground light is

$$E_{xvg} = 0.2 \times \frac{80{,}000 + 9000}{2} = 8900 \text{ lux (827 fc)}$$

STEP 2. Determine net transmittance of the window:

$$\tau = 0.70, \text{ as previously}$$

STEP 3. Select the coefficients of utilization (as was previously done for overcast conditions):

$$\frac{E_{xvk}}{E_{xhk}} = \frac{7500}{9000} = 0.83$$

STEP 4. Calculate the illuminance, using Equation 8.6:

$$\begin{aligned} E_i &= \tau\,(E_{xvk} \times CU_k + E_{xvg} \times CU_g) \\ &= 0.7\,(7500 \times CU_k + 8900 \times CU_g) \end{aligned}$$

Table 8.13 tabulates the illuminances at the five reference locations. ■

8.13 DAYLIGHTING SIMULATION PROGRAMS

Until recently, daylighting simulation tools were too expensive and complex to use on day-to-day designs; they were, as such, primarily utilized by lighting consultants or researchers. Computer rendering tools have been developed so that many simulation programs now provide realistic visual daylighting output with varying degrees of accuracy. Computational approaches can simulate the distribution of light from both daylight and electric sources, for any selected season, time of day, and building location

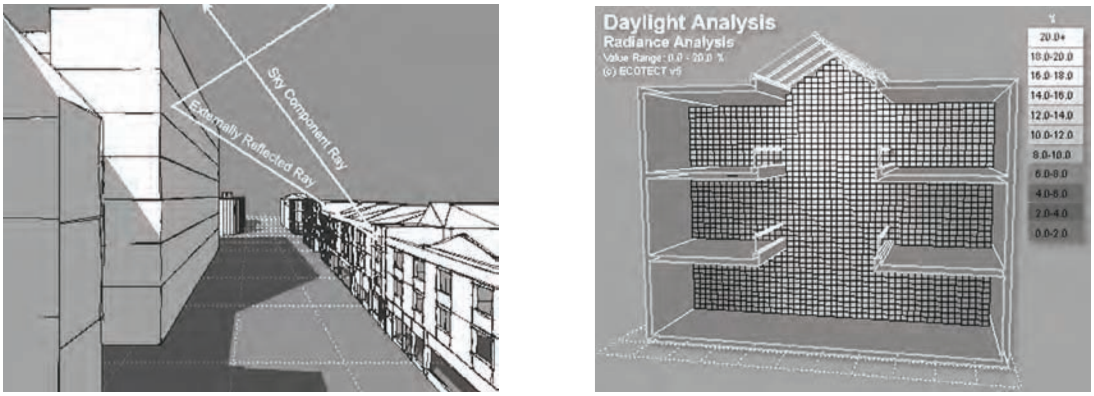
(*a*)

(*b*)

Fig. 8.42 *(a) Rendering of shading provided by the blinds at the* New York Times *building. (b) Rendering study of veiling reflections on a computer monitor. © 2004; example (a) by Greg Ward & Judy Lai; example (b) by Chas Erlich, Lawrence Berkeley National Laboratory, rendered by Radiance; used with permission.*

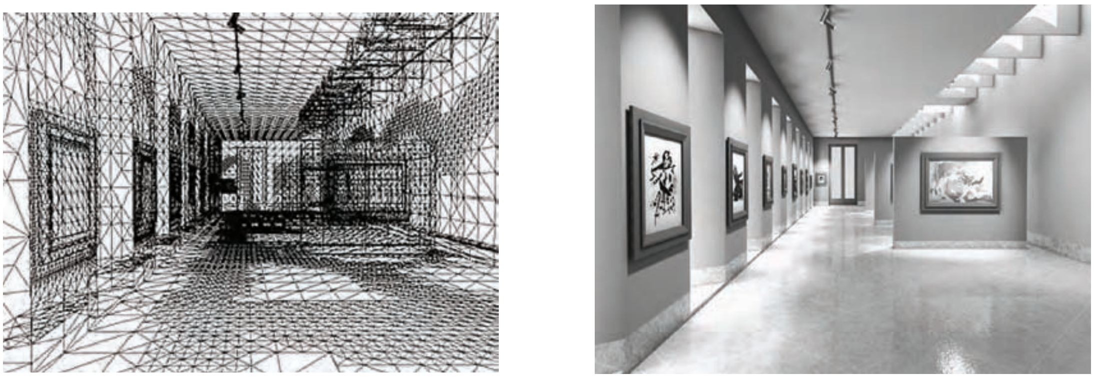
(orientation and latitude). Many of these programs use *radiosity* techniques. Radiosity-based renderings are produced by dividing all the surfaces in a scene into a mesh of small polygons. Each polygon takes on a different value of light absorption/reflection, depending upon its relationship to a light source and its surface parameters. These values simulate the light distribution throughout the scene.

- Desktop Radiance (http://radsite.lbl.gov/deskrad/): Known as Radiance, this program integrates a realistic rendering package (Fig. 8.42) with a computer-aided design (CAD) input environment. Libraries of materials, glazings, luminaires, and furnishings facilitate data entry. Lawrence Berkeley National Laboratory, Pacific Gas and Electric, and the California Institute for Energy and Environment developed this program.
- Autodesk Ecotect Analysis (http://usa.autodesk.com/ecotect-analysis/): This is a building analysis software program offering a range of modeling and analysis features such as visualization, shading, shadows, solar analysis, lighting, thermal performance, ventilation, and acoustics. It can export to Radiance for higher-level ray-tracing techniques. Daylighting capabilities can model shadows and reflections on the surfaces of other buildings at a single point in time, show an entire year's shadow patterns for a single surface, model surface solar radiation relative to the effects on thermal mass, and calculate daylight factor (Fig. 8.43). Ecotect was developed by Dr. Andrew Marsh, and became Autodesk Analysis in 2008; this program is no longer fully supported.
- form•Z RenderZone PLUS (www.formz.com/): Form•Z RenderZone PLUS is a modeling and drafting program with photorealistic rendering. It offers the following three rendering levels: simple, z-buffer, and raytrace. Designs can begin with a 3-D model and gradually add features to render with more complexity. form•Z RenderZone PLUS includes "global illumination" techniques, and produces accurate distribution of light in the environment. form•Z RadioZity is the version of form•Z RenderZone that includes radiosity-based rendering. Lighting conditions can be accurately simulated and incorporated into the rendering. Although familiar to many as an architectural rendering program, it has the ability to accurately show shadows and radiosity rendering (Fig. 8.44).
- Autodesk 3ds Max Design (www.autodesk.com/products/autodesk-3ds-max-design/): Autodesk 3ds Max Design includes 3-D modeling, rendering, and animation. Autodesk VIZ (Fig. 8.45) has migrated to Autodesk 3ds Max Design, which continues to offer a specialized visualization and rendering program that includes lighting effects from indirect illumination and shadows under varying conditions of daylight and electric light, as well as expanded imagery and cinematographic effects.
- AGI32 (www.agi32.com/): Lighting Analysts, Inc. offers this software program for lighting



(*a*) (*b*)

Fig. 8.43 *(a) Schematic output showing exploratory rays passing through a window and hitting an external obstruction. (b) Daylight factor distribution analysis applies a ray-tracing technique using the Building Research Establishment (BRE) Daylight Factor method. (© 2004 Dr. Andrew J. Marsh, of Square One research; created with ECOTECT v5; used with permission.)*



(*a*) (*b*)

Fig. 8.44 *(a) Radiosity rendering of polygons for a gallery space. (b) Rendering of the same gallery space. (© 2004, modeled and rendered with form•Z RadioZity by Markus Bonn, auto.des.sys, Inc.; used with permission.)*

(*a*) (*b*)

Fig. 8.45 *(a, b) Rendering of daylight in a residence. (Certain images reproduced from Autodesk® VIZ Render 2004 software with permission of Autodesk, Inc.; © 2002; all rights reserved.)*

calculations and renderings of electric lighting and daylighting systems. It is widely used in the lighting industry and includes a Web-based interface that allows users to access manufacturers' photometric data and provides for easier updating.

- DFcalc (http://archiphysics.com/programs/daylight/daylight.htm): ArchiPhysics offers this beta-software program to show how daylight is distributed in a room. The program, so far, only calculates the sky component daylight factor for a uniform sky. With simple room dimension and glazing inputs, the program shows daylight distribution on the work plane and daylight factor.
- Rhinoceros with DIVA plugin: (www.rhino3d.com/) 3D modeler software works with a daylighting and energy modeling plug-in—DIVA for Rhino (http://diva4rhino.com/). Initially developed at the Graduate School of Design at Harvard University and now distributed and developed by Solemma LLC, this program offers renderings, glare analysis, daylight factor and illuminance analysis, single thermal zone energy, and load calculations.

8.14 PHYSICAL MODELING

Physical modeling is a useful and indispensable tool for the investigation of complex daylighting phenomena. Simple physical models can give both the designer and the client a visual understanding of a daylighted space. Physical models can duplicate the lighting phenomena that would occur in a full-scale space and, when placed under identical sky conditions, will yield accurate results relative to brightness, shadows, and daylight factor. By changing window design or orientation, adding lightshelves, reflectors, or shading devices, and/or modifying surface materials, a designer can quickly produce a three-dimensional visual image that displays qualitative and quantitative performance results for a proposed daylighting design.

The advantages of physical models include:

- The opportunity for accurate daylight measurements and for qualitative evaluation
- Easy construction (for most designers)
- Crude models that can yield critical information
- Easy comparisons of various schemes (e.g., interchangeable wall or ceiling elements)
- Realistic visualization for clients

The principal disadvantage of using physical models is the need to expose them to the desired sky conditions. For example, waiting for suitable sky conditions in order to view a particular space under both overcast and clear sky conditions, or at different seasons of the year, or during different times of day, is not always practical.

Constructing scale models is relatively simple, using corrugated cardboard, mat board, and colored paper—mounted on a base for ease of manipulation (Fig. 8.46). The model should be made modularly so that alternative design proposals can be interchanged. For example, to compare various skylight configurations, several replaceable roof configurations can be constructed. Model size depends upon the size of photometers used to measure interior illuminance, the size of the space, and the need to accommodate a camera viewport. Considering ease of construction and visualization opportunities, bigger is usually better—although larger models are often preceded by smaller/cruder study models.

Cardboard is an ideal material for daylighting models because it is opaque, unlike foam core board, which is translucent and transmits some light. Unintentional light leaks must be prevented, typically by sealing the joints of a model with black electrician's (or duct) tape or by using strips of black cardboard to close gaps. "Portholes" in one or both of the long sides of a model (approximately 2 in [50 mm] in diameter) will accommodate visual inspection and insertion of a camera lens to photograph the distribution of light. Model surface reflectances (both interior surfaces and exterior surfaces that contribute to daylight distribution) should be the same as those proposed for the actual building (see Table C.27 for reflectances and mat board colors). Special care should be taken to accurately replicate details around daylight openings—the size and depth of mullions, the depth and reflectivity of the sill, louvers, shading devices, and surfaces just outside daylight openings. Any major furnishings that might have a significant impact upon light distribution should also be included.

Daylight model testing may be conducted under a real or an artificial sky and may also involve heliodon studies.

1. Use of a real sky with daylighting models is logical but often difficult to coordinate (as described earlier in this section).

(*a*)

(*b*)

(*c*)

Fig. 8.46 *These photographs illustrate the effectiveness of even a crude model in daylighting studies. (a) A faculty office at the University of California, Berkeley, served as an exercise for a daylighting study. (b) The scale model for this office was constructed of cardboard. Significant reflecting surfaces such as desk surfaces and windowsills were carefully modeled. (c) A quick modification to the model introduced light washing along the wall from a skylight above (upper left of photo) so that the rear of the office would receive more light. All photos were taken on site at midday on an overcast day. (© Alison Kwok; all rights reserved.)*

2. *Artificial sky or mirror box.* Carefully designed and controlled artificial sky domes or a mirror box can duplicate overcast sky conditions with a high degree of accuracy and are ideal for testing physical models. A number of such units exist in major universities and lighting laboratories around the world. Sky domes are usually illuminated by interior perimeter lamps with the model located in the center. A mirror box is essentially a room with a luminous ceiling (using fluorescent lamps) and mirrored walls to create a sky with an "infinite" horizon. For construction details, see Moore (1985).
3. *Heliodon.* The heliodon, as shown in Fig. 8.47, is a sophisticated device that allows the study of shading and solar access at a specific latitude and longitude, time of day, and time of year, using architectural scale models. It operates

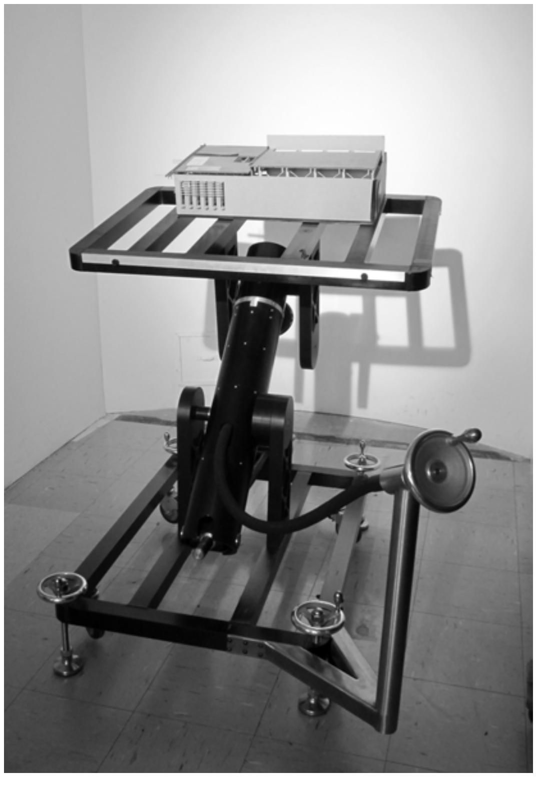


Fig. 8.47 *ShadowTracker heliodon at the Baker Lighting Lab at the University of Oregon. Automated adjustments for latitude, elevation, and tilt permit exposure of the model to desired clear sky conditions. (© Alison Kwok; all rights reserved.)*

by rotating and tilting a building model with respect to the real sky or an "artificial sun" (a narrow-beam electric light source) until the desired solar altitude and azimuth are reached. Over the years, heliodons (*sun machines*, *sun tables*, *helioluxes*, *sun emulators*) have been built using a variety of configurations to simulate the sun's position relative to an architectural scale model. In all cases, the device establishes a geometric relationship for three variables: site location (latitude), solar declination (time of year), and the Earth's rotation (time of day). With an adjustment to any one of these variables, a heliodon can simulate sunlight penetration and shading for any combination of site location and time. Other types of heliodons keep the position of the model fixed and use a band of lamps that move along three axes to simulate the sun's position for different times and seasons.

8.15 RECAPPING DAYLIGHTING

This chapter began by describing the control of daylight in buildings as both an art and a science. Daylighting is a cornerstone of green design and a major contributor to good building energy performance, as well as occupant comfort, productivity, and health. Addressing daylighting early in schematic design is a critical step for successfully zoning activities and massing the building to optimize the use of daylight and minimize the use of electric lighting. Skillfully employing strategies such as toplighting, sidelighting, lightshelves, and shading devices involves numerous qualitative judgments and quantitative calculations to achieve design intents and criteria. While it is important to conduct necessary calculations, it is also important to recognize the beauty in the simplicity of the straightforward design of the past—as shown at the historic Horseshoe Lodge, built in 1939 (Fig. 8.48).

(*a*)

(*b*)

Fig. 8.48 *(a) Shaded walkway at the Horseshoe Lodge, Beulah, Colorado. (b) Sidelighting in dormitory room of the summer camp. (Photos © Dan Bihn; used with permission.)*

8.16 CASE STUDY—DAYLIGHTING DESIGN

The Hive: Worcester Library and History Centre, Worcester, England

Project Basics

- Location: Worcester, England, United Kingdom
- Latitude: 52.2°N; longitude: 2.2°W; elevation: 58 ft (17.7 m)
- Heating degree days: 5866 base 65°F (3259 base 18°C); cooling degree days: 1355 base 50°F (752.3 base 10°C); annual precipitation: 26.3 in. (669 mm)
- Building type: New construction; library
- Building area: 142,654 ft^2 (13,253 m^2) gross floor area divided into four levels
- Completed: January 2012
- Client: WLHC ProjectCo for Worcestershire County Council and the University of Worcester
- Design team: Feilden Clegg Bradley Studios (architects), Max Fordham (services), Hyder Consulting Ltd. (structural); Galliford Try Construction Central (contractors) and specialist consultants

Background and Context. The Hive: Worcester Library and History Centre is an integrated public and university library of Worcester, England. The city's existing library was no longer fit, and the university sought to improve its connection to the city. So, the County Council put forward a proposal of both a public and university library, in order to meet the needs of both Worcester County Council and the University of Worcester. In 2007, a competition included a program for a new building that achieves a 50% reduction in carbon emissions, and fills 50% of its energy needs from renewable sources. The brief also called for the building to have a minimum environmental rating of “Excellent” by the Building Research Establishment Environmental Assessment Method (BREEAM) for buildings. In addition, the building must be able to adapt to the extreme environmental conditions expected in 2050.

Design Intent. Seven golden pyramidal roofs cover an irregular, pentagonal, four-story building plan. The roof profile originates from the surrounding ridgeline of the Malvern Hills and the traditional hop-kiln houses found in the region. The roof cones maximize daylight and provide natural ventilation through a central atrium and a series of voids strategically positioned in the building's various floor plates. The nearby Severn River is used as a heat sink for the cooling system in the library. Biomass from local sources provides the primary heating source.

Design Criteria and Validation. The Hive secured a BREEAM “Outstanding” rating with a score of 86.4% at the final post-construction review. The scheme also exceeds the 50% carbon reduction target, with renewables contributing almost 35% to the reduction. The building is designed to adapt to climate change predicted by the UK Climate Impacts Programme (UKCIP) to 2050. The building has an “A” rated Energy Performance Certificate (given by the government whenever a property is bought, sold, or rented).

Key Design Features

- Daylighting. Skylights with large chamfered surfaces maximize daylight deep into the atrium and down through voids cut into the floor plate. Sidelighting from large areas of shaded vertical glazing supplements the toplighting strategy and ensures an average daylight factor of 3%.
- Natural ventilation. The building is naturally ventilated by air entering through windows at the building perimeter and rising up by the stack effect through the main atrium, then exiting through the roof vents assisted by negative wind pressure. Baffles in the skylights create ventilation troughs that ensure the presence of negative pressure regardless of wind direction. Additional ventilation is delivered to the central atrium via a concrete duct; air travels from an exterior intake vent, under the basement to the base of the atrium, and rises into the atrium.
- Thermal mass. Thermal mass in the concrete soffits stabilizes temperature swings in the library by absorbing heat in the building. During the summer the soffits are precooled by night ventilation that flushes the heat off the concrete and keeps the building cool during the day. During

Fig. 8.49 *Aerial of the site near the Severn River; site diagram showing the massing of the building (Photo by Simon Kirwan; © Simon Kirwan Photography; used with permission.)*

Fig. 8.50 *The Hive is in a historic part of the city of Worcester. It is designed to be an integrated public and university reference and loan library. (© Feilden Clegg Bradley Studios; used with permission.)*

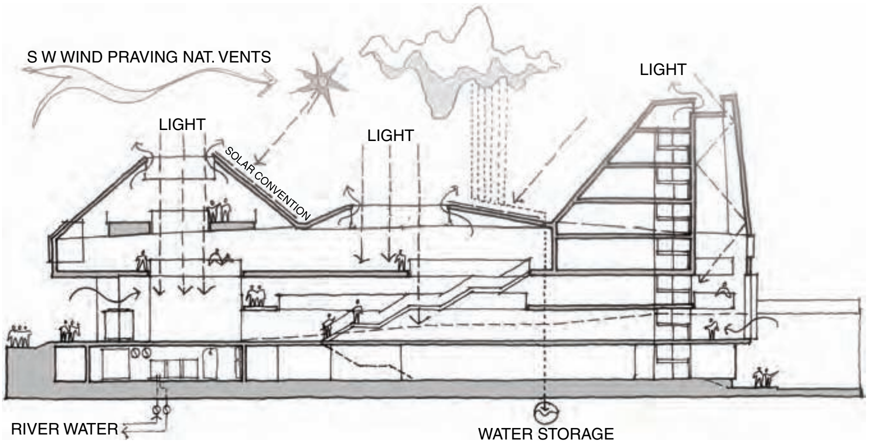


Fig. 8.51 *Early design sketch showing environmental strategies. (© Feilden Clegg Bradley Studios; used with permission.)*

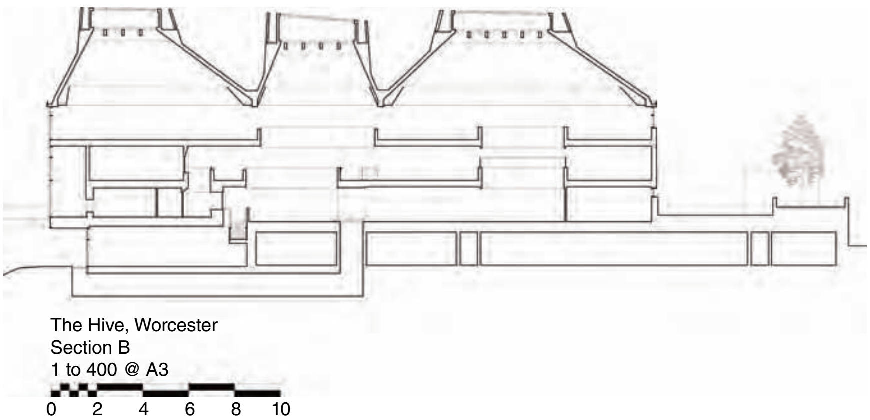


Fig. 8.52 *Section drawing showing roof cowls. (© Feilden Clegg Bradley Studios; used with permission.)*

the winter the soffits absorb daytime radiation and keep the building warm at night.

- Heat sink. The site's proximity to the Severn River allows it to be used as a heat sink. Water is pumped from the river to the building, passes through a heat exchanger and then into radiant coils in the concrete, and is then returned to the river. Piping within the concrete floor cools the structure of the building and provides radiant cooling to occupants. Engineers predicted that the cost of running the water pumps would be a third of the operation costs for conventional HVAC equipment.
- Rainwater harvesting. Water from the rainwater harvesting system is used for flushing toilets and in the wash and silt trap, which forms part of the archaeology service in the history center.
- Alternative energy source. Biomass from local wood chips provides peak heat to the building and further reduces demand on the energy grid.

Post-Occupancy Validation Methods and Performance Data. The public can monitor the building's performance using the display screen in the entrance foyer. Max Fordham has been appointed to carry out additional post-occupancy monitoring and to work with facilities contractor SGP to improve the building performance.

Fig. 8.53 *Daylit atrium is controlled by the structural timber baffles; use of absorptive material around voids in the atrium provides a good acoustical environment. (Photo by Nick Hufton © Hufton & Crow; used with permission.)*

Fig. 8.54 *Rooftop cowls and skylight features. (© photo by Hufton & Crow; used with permission.)*

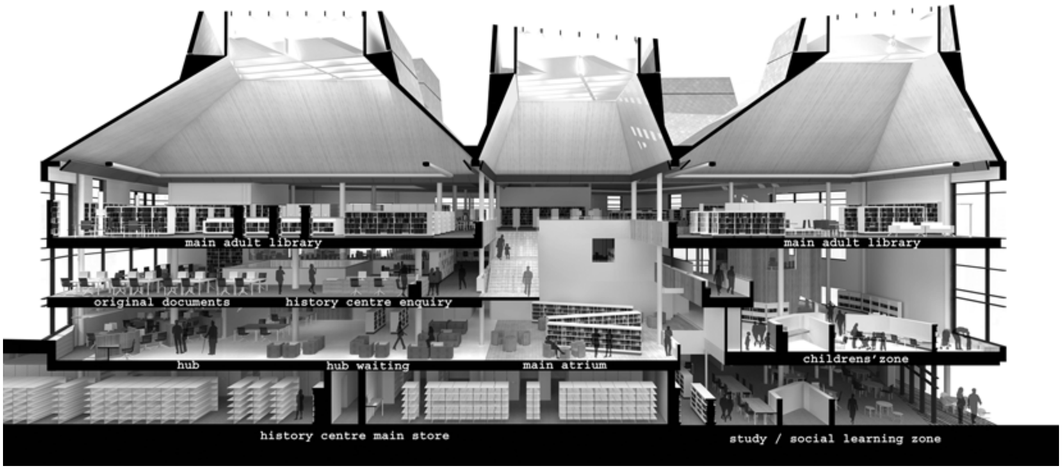


Fig. 8.55 *Section drawing of the building showing the daylight strategy. Baffled skylights allow daylight to wash along the large surfaces, creating a "larger" aperture. (© Feilden Clegg Bradley Studios; used with permission.)*

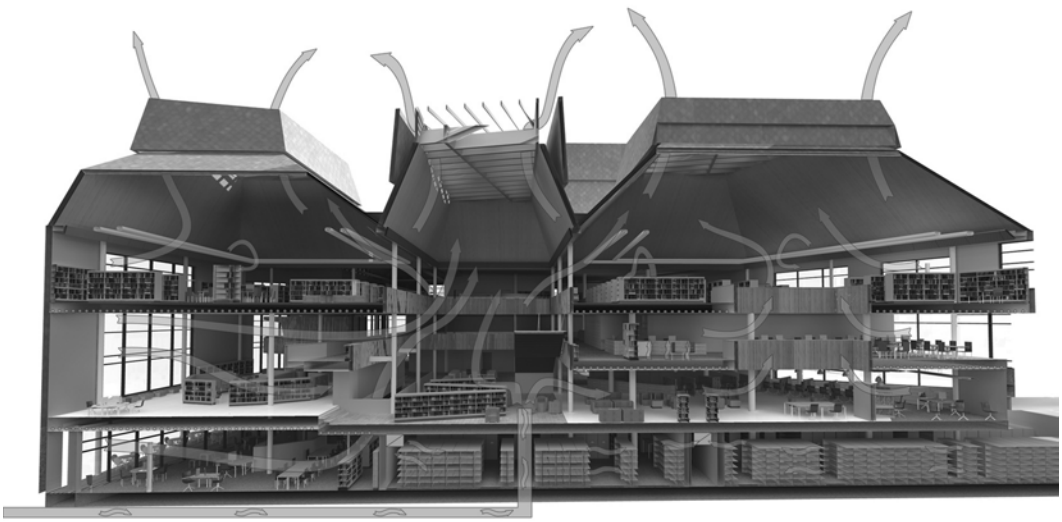


Fig. 8.56 *Section of the building showing the natural ventilation strategy. Air enters around the building perimeter, rises through atria by the stack effect, and exits via the roof cowls under negative wind pressure. (© Feilden Clegg Bradley Studios and Max Fordham LLP; used with permission.)*

Performance Data

- Building Emissions Rate: 3.57/lb CO_2/ft^2 per year (17.4/kg CO_2/m^2 per year).
- Predicted electricity consumption: 9.84 kWh/ft^2 per year (105 kWh/m^2 per year). including small power and IT use.
- Predicted fossil fuel consumption: 0.467 kWh/ft^2 per year (5 kWh/m^2 per year) not including biomass fuel, assumes gas usage for peak loads and backup only.
- Predicted renewable energy generation: 3.561 kWh/ft^2 per year (38 kWh/m^2 per year)
- Predicted water use: 668 gallons (2530 L) per occupant per year; 396 gallons (1500 L) potable water per occupant per year; 264 gallons (1000 L) harvested rainwater per occupant per year.
- Rainwater is projected to supply 40% of the building's water needs.

AWARDS

- 2013 RICS Awards Regional Design and Innovation – Winner
- 2013 RICS Awards Regional Community Benefit – Winner
- 2013 RIBA Awards National – Winner
- 2013 RIBA Awards Regional Sustainability Award – Winner
- 2013 Building Awards: Sustainability Project of the Year – Winner
- 2013 Civic Trust Awards – Winner
- 2013 CIBSE Building Performance Awards: New Build Project of the Year (value above £5 million) – Winner
- 2012 PFI Partnership Awards: Best Sustainability in a Project
- 2012 Wood Awards: Commercial & Public Access: Shortlist
- 2012 Partnerships Awards: Best Community Project: Shortlist
- 2012 Partnerships Awards: Best Sustainability in a Project – Winner
- 2012 Partnerships Awards: Best Pathfinder Project: Shortlist
- 2012 Partnerships Awards: Best Local Government Project Team: Shortlist
- 2012 Partnerships Awards: Best Designed Project: Shortlist
- 2012 WAF Awards: Culture – Libraries: Shortlist
- 2009 Bentley Awards – Be Inspired: Infrastructure Best Practices Symposium and Awards: Innovation in Generative Design – First Prize

FOR FURTHER INFORMATION

Feilden Clegg Bradley Studios: http://www.fcbstudios.com/

Max Fordham LLP: http://www.maxfordham.com/

"The Hive / Feilden Clegg Bradley Studios," *ArchDaily*. April 13, 2012: http://www.archdaily.com/225962

"The Hive by Feilden Clegg, Bradley Studios," *De Zeen Magazine*. April 12, 2012: http://www.dezeen.com/2012/04/12/the-hive-by-feilden-cleggbradley-studios

"The Hive Library Worcester": http://designalmic.com/the-hive-library-worcester-feilden-clegg-bradley-studios

Pearson, Andy. 2013. "The Hive – the UK's first fully integrated public and university library." *CIBSE Journal*, March 2013. https://www.cibseknowledgeportal.co.uk/the-hive

The Hive: Worcester Library and History Centre (project archive): http://www.wlhc.org.uk

References and Resources

American Institute of Architects. 2012. *An Architect's Guide to Integrating Energy Modeling in the Design Process*. Washington, D.C. http://www.aia.org/practicing/AIAB097932

Brown, G. Z. and M. DeKay. 2000. *Sun, Wind & Light: Architectural Design Strategies*, 2nd ed. John Wiley & Sons. New York.

Bryan, H. and S. M. Autif. 2002. "Lighting/Daylighting Analysis: A Comparison." *Proceedings of the National Solar Energy Conference*. American Solar Energy Society. Boulder, CO.

CIE. 1970. *Daylight: International Recommendations for the Calculation of Natural Daylight* (Publication No. 16 E-3.2). Commission Internationale de l'Eclairage. Paris.

DeKay, M. 1992. "Volumetric Implications and a Rule-of-Thumb for Thickness of Atria Buildings." *Proceedings of the 17th National Passive Solar Conference*. American Solar Energy Society. Boulder, CO.

Dresler, A. 1963. *Daylight Design Diagrams*. Service Division, Commonwealth of Labor and National Service. Melbourne, Australia.

Heschong Mahone Group. 1999–2003. Executive summaries and reports available from: http://www.h-m-g.com/downloads/Daylighting/order_daylighting.htm

Hopkinson, R. G., R. Pethebridge, and J. Longmore. 1966. *Daylighting*. Heinemann. London.

IESNA. 1994. *Recommended Practice for the Calculation of Daylight Availability* (RP-21-84; reaffirmed

1994). Illuminating Engineering Society of North America. New York, NY.
IESNA. 1999. *Daylighting* (RP-5-99). Illuminating Engineering Society of North America. New York, NY.
IESNA. 1989. *Recommended Practice for the Lumen Method of Daylight Calculations* (RP-23-89). Illuminating Engineering Society of North America. New York, NY.
International Energy Agency. 2000. *Daylight in Buildings: A Source Book on Daylighting Systems and Components*. International Energy Agency, Solar Heating and Cooling Programme, Energy Conservation in Buildings and Community Systems. Berkeley, CA.
Krochman, J. 1963. "Über die horizontal Beleuchtungsstärke der Tagesbeleuchtung." *Lichtechnik*, Vol. 15, no. 11.
Lam, W. 1986. *Sunlighting as Formgiver for Architecture*. Van Nostrand Reinhold. New York, NY.
Lawrence Berkeley National Laboratory. "Windows and Daylighting." http://windows.lbl.gov/
Lighting Design Lab (Seattle): http://lightingdesignlab.com/
Millet, M. S. and J. R. Bedrick. 1980. *Graphic Daylighting Design Method*. Lawrence Berkeley Laboratory/U.S. Department of Energy. Washington, DC.
Moore, F. 1985. *Concepts and Practice of Architectural Daylighting*. Van Nostrand Reinhold. New York.
National Institute of Building Sciences. *Whole Building Design Guide.* "Daylighting." http://www.wbdg.org/resources/daylighting.php/
Rennhackkamp, W. M. H. 1967. "Sky Luminance Distribution in Warm Arid Climates." Proceedings 16th International Conference on Illumination, Washington, DC.
Stein, B. and J. Reynolds. 1992. *Mechanical and Electrical Equipment for Buildings*, 8th ed. John Wiley & Sons. New York.

CHAPTER 9

Passive Heating

Passive heating systems harness short-wave radiation from the sun to provide the majority of the heating demand in building interiors. This approach is called "passive" because it is accomplished without the use of "active" systems such as mechanical systems with fans and pumps, which are described in Chapter 12. The two primary advantages of passive heating systems are that they substitute free solar energy for purchased energy, and their components perform multiple functions in the building (envelope, structure, and heat storage together) rather than having a single purpose only. A variety of strategies can be used to perform the three main functions inherent in any passive heating system: collecting solar energy directly (south-facing glazing) or indirectly (using components such as sun spaces or Trombe walls); storing or absorbing the energy using masonry, water, or special phase-change materials, which have large thermal storage capacities; and releasing the energy later in the day when it is needed.

The information in this chapter is organized from general to specific. General guidelines are given as a starting point for preliminary passive heating sizing for typical buildings; these include determining solar opening size, thermal mass, and the solar savings fraction (SSF). Designers can make quick approximations to determine if the design is on the right track. As the building takes shape, more detailed information becomes useful, and a section with more detailed calculation procedures will allow the designer to select a passive solar heating approach with some confidence in its applicability and the need for auxiliary space heating. A number of example exercises and solutions for the various strategies will demonstrate how to start making these schematic design calculations.

9.1 BRIEF HISTORY

There exists a rich history of passive heating traditions throughout the world. While passive heating strategies have been used for thousands of years, their application appears to follow a cyclical trend in which periods of great interest are followed by periods of indifference.

The Greeks are thought to be among the first civilizations to design buildings for passive heating potential. They collected and stored solar energy, but were unable to retain the heat at night because window openings were unglazed. This is the classic "leaky box" scenario. The Romans, in typical Roman fashion, took ideas from the Greeks and improved upon them, principally by providing window glazing. Vitruvius even wrote about a passive heating component similar to a modern-day sunspace, which he called the *heliocaminus*.

In the period that followed the fall of the Roman Empire, interest in passive heating declined in Europe. However, around that time, Native American communities in the American Southwest were exploring passive heating strategies in their pueblos and cliff-dwellings with a strong emphasis on building orientation.

A resurgence of interest in passive heating occurred in seventeenth-century Europe following exploration of distant lands. Aristocrats in cold climates built glazed conservatories attached to their homes in order to grow the exotic plants and fruits brought back from abroad. These structures acted as sun spaces that helped heat the main house in addition to serving as greenhouses for botanicals.

Interest in passive heating waned again during the Industrial Revolution, but reemerged during the early twentieth century with the modern movement in architecture. Proponents of passive strategies such as Marcel Breuer and Walter Gropius of the Bauhaus school in Germany introduced these design concepts to America when they relocated prior to WWII. A new generation of architects interested in passive solar design emerged around this time, including George Fred Keck in Chicago.

In 1943 Frank Lloyd Wright designed the Hemicycle House in Madison, Wisconsin, which was one of the earliest houses to incorporate the fundamental elements of passive solar design that we still use today. The house was oriented with its long façade due south, with broad overhangs to shade the south glazing during the cooling season, large areas of glazing for solar collection during the heating season, minimal window openings on the other facades, insulated exterior walls, and concrete floor slabs for thermal mass.

Cheap fossil-fuel-based energy following the end of World War II resulted in a lack of interest in passive solar heating systems, but the energy crisis of the 1970s became an enormous catalyst for an architectural movement focused on energy efficiency in buildings. Demonstration houses by Doug Balcomb in Santa Fe, New Mexico, and Doug Kelbaugh in Princeton, New Jersey, explored the potential of integrating a variety of different passive solar components, and publications such as Edward Mazria's seminal *The Passive Solar Energy Book* assisted other designers in mastering the basics of solar design.

More recently, the green building movement has rekindled interest in passive heating systems. The design components and concepts have changed little, but the scale of the buildings being designed and constructed to use them has increased—for example, the Beddington Zero Energy Development (BedZED) housing development (Fig. 9.1).

9.2 DESIGN STRATEGIES FOR HEATING

The three fundamental solar heating approaches are *direct gain* (let sunlight into the space, where it warms exposed thermally massive surfaces), *indirect gain* (sun strikes the thermal mass first and is then passed only as heat to the space behind), and *isolated gain* (a sunspace or greenhouse heated greatly by the sun that then passes some of its heat to the space behind). Direct-gain systems carry the symbol DG; indirect-gain systems, TW (for Trombe wall), WW (for water wall); isolated-gain systems, SS (for sunspace). For more details, see Appendix I.

(a) Direct Gain

Almost any building with some south-facing glass could claim to be a direct-gain building. The sun is admitted to the space to be heated, striking furnishings and room surfaces. In a well-designed direct-gain space, there are ample thermally massive surfaces (such as concrete slab; concrete block; or brick, quarry, or ceramic tile) that directly receive much of this incoming sun. Such massive surfaces should have at least three times the area of south-facing glass in order to keep the space from overheating during sunny hours. The mass should be thick enough, typically at least 4 in. (100 mm), to absorb and later reradiate a winter day's dosage of direct sun. Appendix I includes variations on direct-gain approaches that involve glazing types, relative mass areas and thickness, and whether night insulation is used over windows.

Direct gain is popular because of its simplicity and its ample daylight and view to the south. Relative to the other passive solar approaches, it has problems of glare, overheating on sunny days, large radiant heat losses to glass areas by night (and thus a large diurnal difference in interior temperature), and fading of furnishings in direct sunlight. This winter heating approach is well matched with the summer cooling strategy of night ventilation of mass; both systems depend on large areas of internal exposed thermal mass, so such an investment pays off in both winter and summer.

(b) Indirect Gain

This is the passive solar approach encountered least often, perhaps because a sheet of glass covering an

Fig. 9.1 *Beddington Zero Energy Development (BedZED) concept is to provide housing that makes it possible for a UK citizen to live within a 4.7-acre (1.9-ha) ecological footprint. The neighborhood uses a number of passive strategies: sunspaces in residential units, thermal zoning for comfort and daylight access, exposed thermal mass, and natural ventilation, to name a few. (© Alison Kwok; all rights reserved.)*

opaque wall seems such a denial of "window." The mass wall behind the glass is usually 8 to 12 in. (200 to 300 mm) thick, and should be of a dense and highly conductive material such as standard-weight concrete or dense brick. Water in containers can also be used as an option for mass. An air space between the glass and the mass allows for the option to "vent" the mass wall, whereby cool air from the heated space behind the wall enters at the bottom, rises with solar heating, and then exits into the space behind, near the ceiling. Sometimes this air space is made wide enough to admit a person for cleaning the inside surface of the glass, but operable casement or awning-type glazings are other cleanable options. The back surface of the mass (facing the heated space) should be kept clear of hangings or large furniture, to facilitate radiant heat transfer to the space. Appendix I includes variations on indirect-gain approaches involving mass characteristics (water or masonry), thickness, and surface treatments; whether masonry walls are vented; glazing types; and whether night insulation is used behind the glazing.

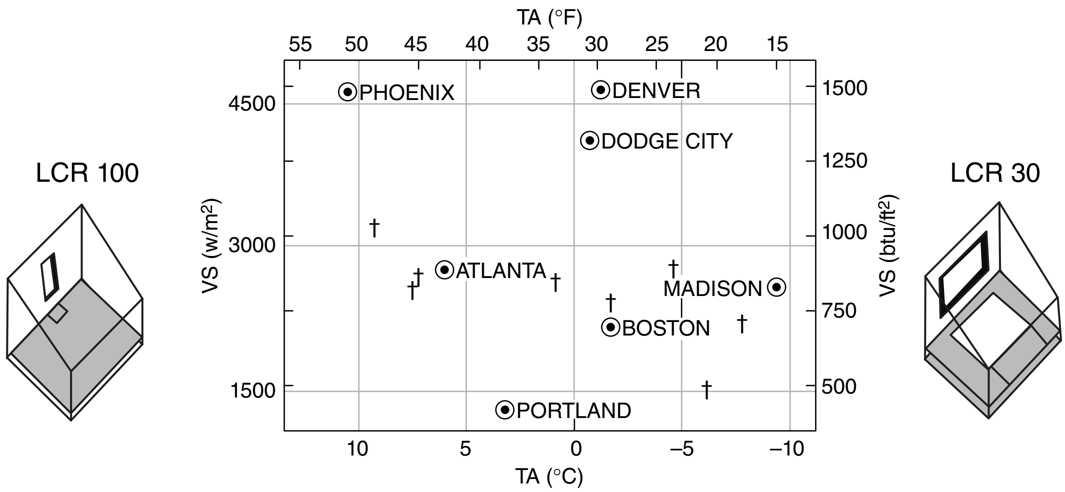
Indirect gain is less popular than direct gain because, typically, the system blocks daylight and views to the south. Yet, relative to the other passive solar approaches, it has advantages of less glare, significantly less overheating on sunny days, and no fading of furnishings in direct sunlight. Another advantage is its large radiant heat contributions in the evening after sunny days. Many applications of indirect gain incorporate a smaller area of direct gain (window) within the larger indirect-gain wall surface.

(c) Isolated Gain

This is a popular passive solar approach because it provides a sunny habitable space, alternately called a *sunspace*, *greenhouse*, *sun room*, or *winter garden*. This space experiences great variations in temperature—hot in the afternoon, cold before dawn—to allow the space behind it to be kept reasonably comfortable with solar heating delivered as needed. The sunspace usually has both south-facing vertical glazing and inclined glazing, increasing insolation in both winter and summer. Appendix I contains variations on isolated-gain approaches that involve configurations of the glazings; whether the sunspace is surrounded by the building or is added on; whether the common wall between sunspace and building is masonry or insulated frame; whether the sunspace's end walls (facing east and west) are glazed or insulated; glazing types; and whether night insulation is used behind the glazing.

Figure 9.2*a* compares the contribution of solar space heating to a building during the winter months, in seven North American cities, plotting the points of *TA* (average January ambient dry-bulb temperature) and *VS* (average January daily solar radiation on a vertical south-facing surface). Sunny and cold Denver, Colorado, contrasts sharply with cloudy and cool Portland, Oregon. Yet, the subsequent charts show that even in Portland, solar energy can contribute to space heating. Refer to Table C.19 to find the values for these and other locations.

The remainder of Fig. 9.2 compares two building envelope types with three common solar heating strategies. The left column (Fig. 9.2*b*, *d*, *f*) assumes a building with insulation at code-required minimums and some south-facing glass (unshaded in winter). For this modestly-solar building type, the seasonal fuel bill will be reduced, but rarely more than 40%, by using solar energy. The right column (Fig. 9.2*c*, *e*, *g*) assumes a building that exceeds minimum insulation requirements and is designed with much greater areas of south-facing glass unshaded in winter. For this seriously-solar building type, the seasonal fuel bill will be reduced by about twice as much as its modest counterpart.



(*a*)

Fig. 9.2 *Early assessment of passive solar heating potential. (a) From Tables C.19 and C.20, the January TA (average air temperature) and January VS (daily solar radiation on a vertical surface) are plotted for Atlanta, Georgia; Boston, Massachusetts; Denver, Colorado; Dodge City, Kansas; Madison, Wisconsin; Phoenix, Arizona; and Portland, Oregon. The solar savings fraction (SSF), the percentage reduction in heating fuel achieved by a passive solar design, is approximated for modestly-solar "LCR 100" (smaller south windows, moderately well insulated) and seriously solar "LCR 30" (larger south windows, very well insulated) buildings. († Indicates where SSF is approximately 6% higher than that shown on the graph for these locations: in California: Fresno, Mt. Shasta, Sacramento, and San Francisco; in Idaho: Boise and Pocatello; in Montana: Helena and Missoula; and in Nevada: Reno.) (b) Direct-gain systems in modestly-solar buildings; (c) in seriously-solar buildings. (d) Indirect-gain systems in modestly solar buildings; (e) in seriously-solar buildings. (f) Isolated-gain systems in modestly-solar buildings; (g) in seriously-solar buildings.*

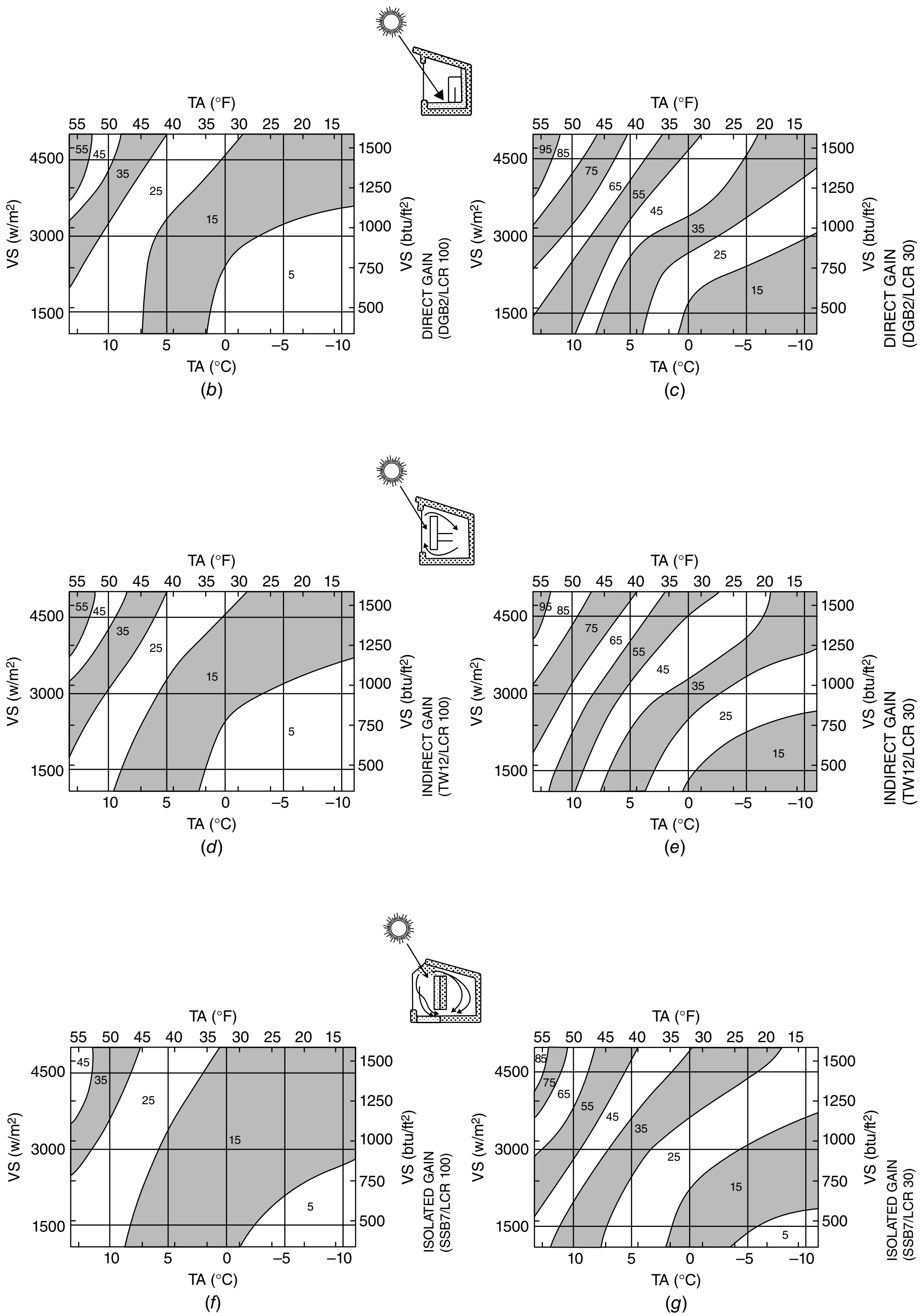


Fig. 9.2 *(Continued)*

9.3 GUIDELINES: PASSIVE SOLAR HEATING

When the building's function, climate, and site are favorable, winter solar gains can contribute greatly to a properly designed building. One of the first criteria to be considered is energy conservation—a poorly insulated building will be expensive to heat; there is little benefit in pouring solar heat into a leaky building. Heat loss must be balanced with heat gains in order to maintain comfortable temperatures. For passive design, the motto should be "Insulate before you insolate."

(a) Whole-Building Heat Loss Criteria

The recommended maximum rates of heat loss (in Btu per degree days [DD] per square foot) shown in Table 9.1 are the basis for development of the following passive solar heating guidelines. They are also useful as a quick check on overall envelope performance in residential or small commercial buildings. (Some states have adopted similar criteria as part of their building codes; be sure to check the applicable code before relying on these numbers for code compliance.) The heat loss rates are shown for two conditions:

1. *Conventional (not passively solar-heated) small buildings.* The overall rate of Btu/DD ft^2 is based on *total* heat loss, including all portions of the envelope *and* infiltration. To determine the whole-building heat loss rate, list for each envelope component (roof, walls, floor, windows, etc.) the U-factor (Chapter 7 and Appendix E) and the total exposed area *A*; then simply multiply U × A. (For slab floors on grade, see Chapter 7 for determining perimeter heat losses.) For the special cases of walls below grade, such as berm walls, an approximation is needed. During the coldest weather, the temperature outside such walls will nearly always be higher than the outdoor air temperature, so any procedure based on Btu/DD will *overpredict* the heat loss through these walls. As a result, designers often calculate the UA of below-grade walls by using their actual U-factor but using only *half* of their actual area; this lesser A roughly compensates for the lesser Δt through these walls.

   For infiltration, determine the number of air changes per hour (ACH) under winter design conditions and multiply this infiltration (or fresh air) rate by a constant that accounts for density and specific heat:

$$\left.\begin{array}{l}\text{ACH}\quad(\text{volume, m}^3)\times 0.33 = \\ \text{or}\quad \text{ACH}\,(\text{volume, ft}^3)\times 0.018 = \end{array}\right\}\ UA \text{ for infiltration}$$

   Add the envelope UA values to those for infiltration, multiply by 24 h/day to account for DD, and divide by the building's total heated floor area (the same applies for SI units):

$$\frac{(UA_{\text{envelope}} + UA_{\text{infiltration}})\times 24\ \text{h}}{\text{total heated floor area (ft}^2)} = \text{Btu / DD ft}^2$$

2. *Passively solar-heated buildings.* Here the overall rate of Btu/DD ft^2 *excludes* the solar collecting portion(s) of the envelope; otherwise, it is based on total heat loss from all other portions of the

TABLE 9.1 Overall Heat Loss Criteria for Solar Guidelines

Maximum Overall Heat Loss					
		Btu/DDF ft²		*W/DDK m²*	
Annual Heating Degree Days					
(Base 65°F)	**(Base 18°C)**	**Conventional Buildings**	**Passively Solar-Heated Buildings, Excluding Solar Wall[a]**	**Conventional Buildings**	**Passively Solar-Heated Buildings, Excluding Solar Wall[a]**
Less than 1000	Less than 556	9	7.6	51	43
1000–3000	556–1667	8	6.6	45	37
3000–5000	1667–2778	7	5.6	40	32
5000–7000	2778–3889	6	4.6	34	26
Over 7000	Over 3889	5	3.6	28	20

Source: Balcomb et al. (1980). SI conversions approximated by the authors of this book.

[a]The guidelines in Table G.1 assume a solar building that meets this criterion.

envelope, and it includes infiltration. The equation (in I-P units) used to determine the overall rate is as follows:

$$\frac{(UA_{\text{envelope, except south glass}} + UA_{\text{infiltration}}) \times 24\text{ h}}{\text{total heated floor area (ft}^2\text{)}} = \text{Btu / DD ft}^2$$

One of the biggest unknowns in this procedure is the assumed rate of infiltration. A carefully designed and constructed small building can easily achieve a rate of 0.75 ACH; with increased attention to air barrier installation, caulking of all cracks, and so on, rates below 0.33 ACH have been demonstrated.

Passive solar heating and energy conservation have a complex relationship. Relative to conventional buildings, passively solar-heated buildings usually conserve purchased energy; yet, buildings that aim at very high percentages of solar heating can use more *total* heating energy than is used by buildings with smaller window areas. Designers interested primarily in saving purchased energy may aim at lower solar percentages and more insulation; designers interested in buildings that closely relate to climate and climatic changes may aim at higher solar percentages (and more daylighting), along with higher thermal masses and, probably, greater ranges of indoor temperature.

(b) Solar Savings Fraction (SSF)

The term *solar savings fraction* is used to express a building's solar heating performance. The SSF is the extent to which a solar design *reduces a building's auxiliary heat requirement* relative to a "reference" building—one that has, instead of a solar wall, an energy-neutral wall that experiences neither solar gain nor heat loss; otherwise, the solar building and the reference building are identical. The SSF compares the auxiliary energy needed by the solar building to the auxiliary energy needed by the reference building, as illustrated in Fig. 9.3. Remember that the SSF is *not* the percentage of the solar building's heat supplied by the sun; typically, the sun provides a much *higher* fraction of a building's total space heat than suggested by the SSF. Rather, the SSF is more a measure of the solar building's *conservation* advantage.

A starting point for passive solar preliminary design is Table G.1. For your location, both a range of SSF values and a range of ratios of areas of south glass/floor area can be determined. The table shows the SSF ranges for both "standard performance" (simple double-glazed windows) and "superior performance" (for either night-insulated or superwindow) solar openings. This same information is shown graphically for six geographically diverse locations in Fig. 9.4. (Add your own location's information from Table G.1 to a copy of this graph.)

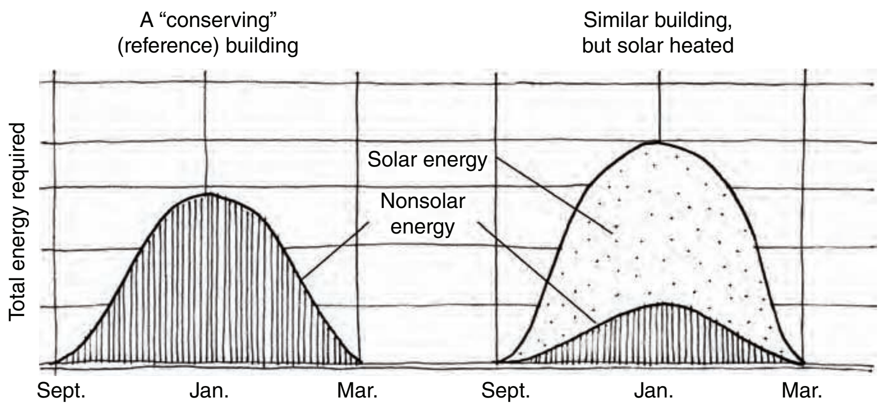


Fig. 9.3 *The solar savings fraction compares the auxiliary heat needed by solar-heated buildings to that needed by a nonsolar but energy-conserving building that is otherwise similar, called the "reference" building. For example, if the solar building needs 25 units of auxiliary heat per year and the reference building needs 70 units, the difference is 70 – 25 = 45 units, or 64% of the reference 70 units. Therefore, SSF = 64%. (Note, however, that the solar building is 75% solar heated.) (From Brown, Reynolds, and Ubbelohde,* Inside Out: Design Procedures for Passive Environmental Technologies*; © 1982, John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc. Redrawn by Erik Winter.)*

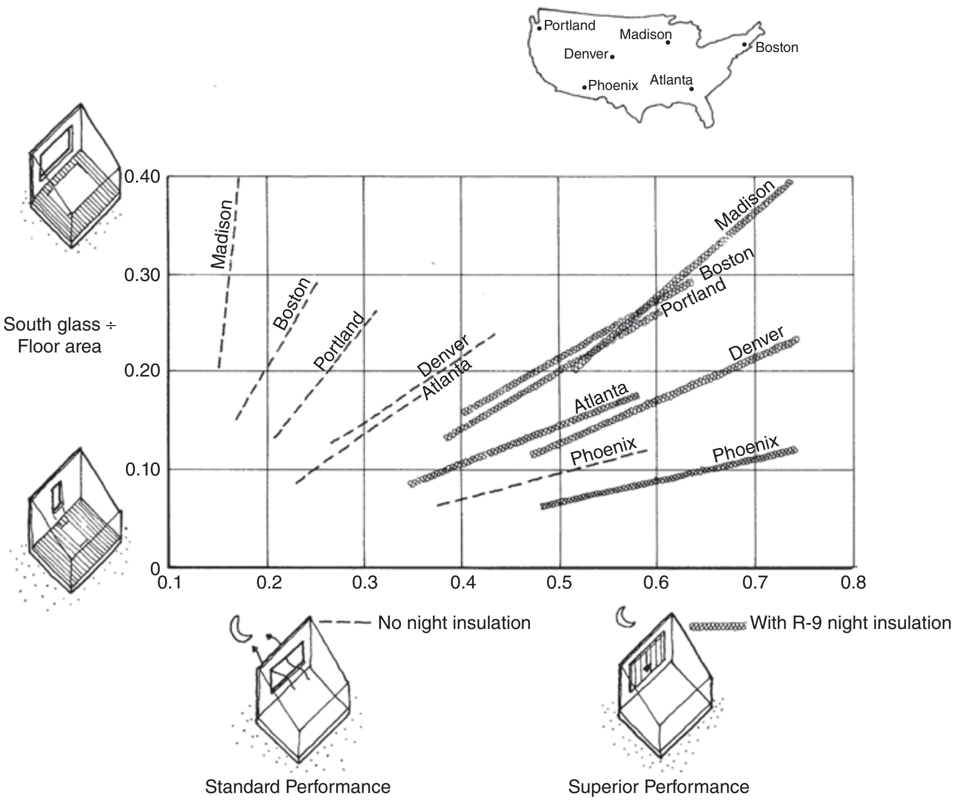


Fig. 9.4 *Design guidelines for passive solar heating: ratio of south glass to floor area. The information in Table G.1 is presented graphically for six U.S. cities. "No night insulation" = standard performance; "With R-9 night insulation" = superior performance.*

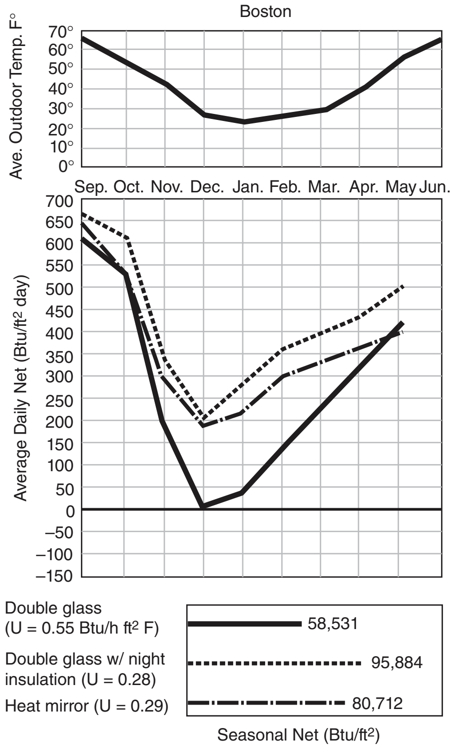
The difference between standard and superior performance is explored in Fig. 9.5 for the September–June period in Boston, Madison, and Seattle. The solid line charts the lower performance of simple double glazing (listed as U = 0.55 Btu/h ft^2 °F [U-SI = 3.1]). The other two higher-performance alternatives (movable insulation and superwindows) show why the newer superwindows have made movable insulation nearly obsolete: Without the need for any actions by the user, superwindows have a higher net heat gain than movable insulation in all three locations.

(c) Thermal Mass

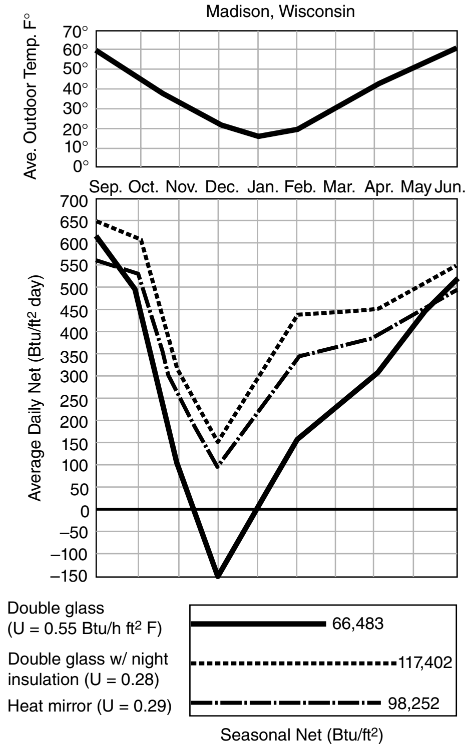
Another early design question involves the amount of thermal mass area necessary to store the solar heat admitted each day. This reveals the simplistic, early-design nature of Table G.1, because it does not distinguish between the various approaches to passive solar heating (*direct gain*, *indirect gain*, and *isolated gain*). Table G.2 details the simple relationship between SSF and the area (also the weight) of water or masonry that should be provided in direct-gain designs.

The *distribution* of the thermal mass is also important, however. Indirect gain systems (Trombe wall and water wall systems) usually place the thermal mass in full sun for the entire day, often just inside the glazing. In direct-gain systems, this thermal mass should be within (or should enclose) the direct-gain–heated space, and the exposed surface area of the mass should be *at least three times the glazing area*. Masonry surfaces are less thermally effective (on a daily basis) beyond a depth of about 4 to 6 in. (100 to 150 mm). Note that the thermal storage area is relatively unimportant at low SSF values, but as the SSF increases, so does the relative proportion of thermal mass area to solar glazing.

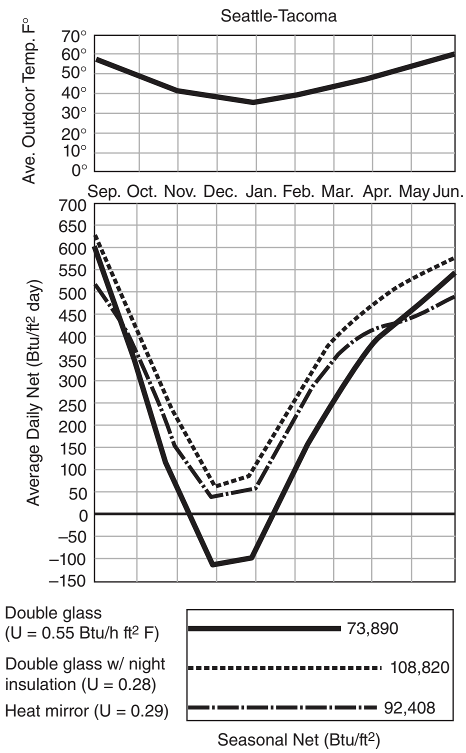
Phase-change materials are an alternative to simple thermally massive masonry surfaces. Flat



(*a*)



(*b*)



(*c*)

Fig. 9.5 *Average daily net heating, per square foot of south window, for three glazing assemblies in three climates. (a) In Boston, ordinary double glazing is a slight energy plus even in December. (b) In Madison, ordinary double glazing is a net loser for almost 2 months. (c) In Seattle, ordinary double glazing is a net loser for more than 2 months. (From Johnson, 1981.)*

bags of eutectic salts are shown in Fig. 9.6. Thin, horizontal tiles packed with these phase-change materials can store great quantities of heat with the phase change from solid to liquid. This change can be formulated to occur in the low 70s °F (20s °C) to prevent overheating of the space. As flat tiles enclosing bags of salt, they can form the finished surface in any horizontal application—floors, ceilings, or counter tops/tabletops, for example. Tubes and trays of salts can be arranged as desired. Because the function of these materials is to keep room temperatures steady, their performance in preventing overheating on a sunny winter day will also be appreciated on hot summer days, provided they are taken below the phase change or melting temperature at night. For U.S. locations with large daily temperature ranges in summer (see example mean daily range values in Appendix B), thermal

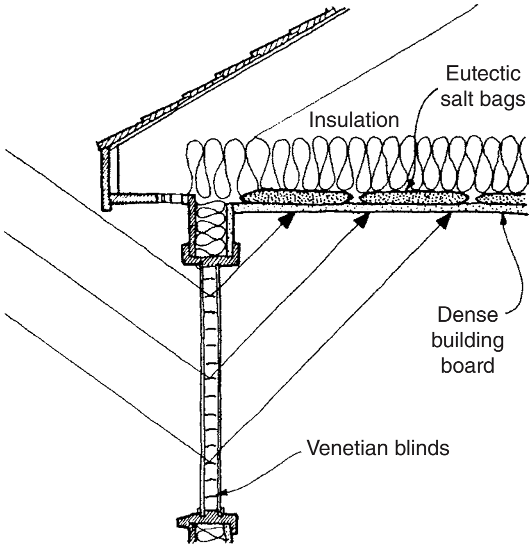


Fig. 9.6 *Using bags of phase-change material (eutectic salt) for thermal storage above a flat ceiling. Mirrored-surface venetian blinds reflect direct solar radiation to the ceiling, where it strikes a heavy (at least 90 lb/ft² [440 kg/m²]) board product with high conductivity. Metal ceilings or plaster are also suitable; ordinary gypsum board is not sufficiently conductive. Bags of salt weighing 5 lb/ft² (25 kg/m²) are in contact with the ceiling material and must be installed in a horizontal position. They are usually formulated to melt between 70 and 75°F (21 and 24°C). (Adapted by permission from Johnson, 1981.)*

storage surfaces for passive solar heating in winter are potentially useful for night ventilation cooling in summer.

As a preliminary guide, *the phase-change tile surface area = one to three times the area of solar opening*. Additional information on these materials can be found in Johnson (1981).

The Society for the Protection of New Hampshire Forests building utilizes phase-change storage above a metal ceiling (Fig. 9.7). It also uses water-filled tubes as an interior partition, masonry interior walls, and a concrete floor slab to help store the winter daily solar gain.

The New Canaan Nature Center (Fig. 9.8) is another innovative New England example using many passive/low-energy components. In addition to eutectic salts used in the south-facing railing on the upper level, the 4000-ft^2 (372-m^2) building utilizes extensive clear, double-glazed south glass, movable insulating shades, operable vents at the skylight for stack-effect ventilation, ceiling fans, a woodstove, solar collectors placed inside the skylight monitor (their water is used for warming planting beds), warm air heat recovery ducts, a well-insulated envelope, and even a rainwater collection system. The manually operated switches for ventilation, insulation, and shading represent an unusual degree of user–building interaction. There is also unusual attention to microclimates and the transition between inside and outside in this award-winning building.

Rock beds are sometimes used to store the excess heat that isolated-gain (sunspace) systems can generate. They are typically placed directly beneath a concrete floor slab. The disadvantage of this approach is that any below-grade location raises suspicions of condensation and/or groundwater that may facilitate mold growth, while cleaning of the rock bed is difficult.

The general guidelines cited by Mazria (1979) are as follows:

Rock bed volume, ft³, per ft² of solar opening

Cold climates: ¾ to 1½

Temperate climates: 1½ to 3

Rock bed surface area in contact with floor above

Cold climates: 75% to 100% of floor area above

Temperate climates: 50% to 75% of floor area above

(d) Orientation

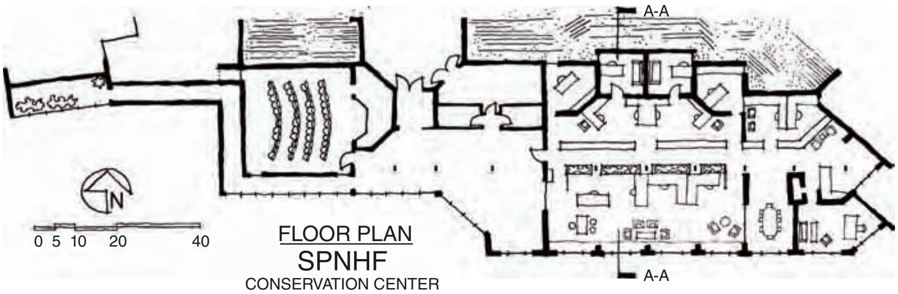
How important is it that the passive solar opening face due south? The general recommendation is that this orientation be *within 30° of south*. In *The Passive Solar Design Handbook* (Balcomb et al., 1980), the average penalties for off-south orientation are listed as follows.

5% decrease in SSF at 18° east or 30° west of true south

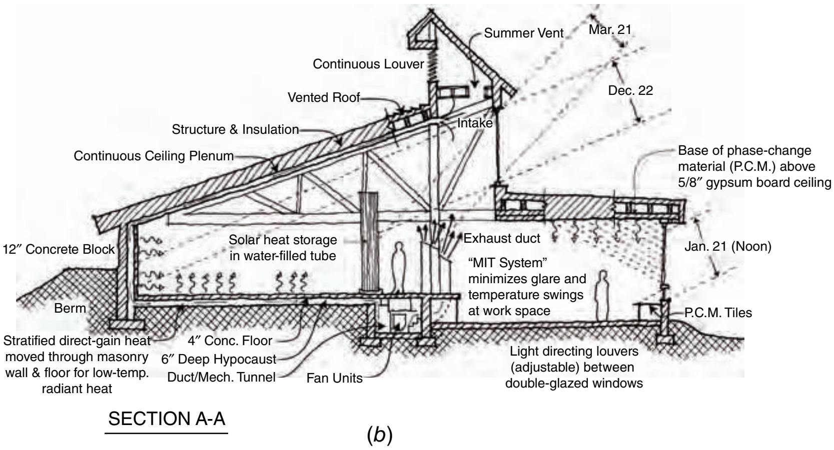
10% decrease in SSF at 28° east or 40° west of true south

20% decrease in SSF at 42° east or 54° west of true south

See Section 9.6 for more detailed coverage of passive heating performance that distinguishes among direct, indirect, and isolated gain systems and includes the expected annual auxiliary energy needed by a passively solar-heated building.



(*a*)



(*b*)

(*c*)

Fig. 9.7 *The Conservation Center for the Society for the Protection of New Hampshire Forests, Concord, Banwell White Arnold Hemberger & Partners, Architects. (a) The plan is elongated on the east–west axis to maximize southern exposure and facilitate daylighting. Direct gain serves the reception area, workroom, and offices, and a sunspace double-envelope combination warms the lecture room. A wood-fired boiler provides backup heat. (b) Section with south glazing and thermal storage materials: translucent water tubes, masonry walls, and phase-change materials in ceiling and windowsill positions. The circulation of hot air that collects at the clerestory is also shown. In summer, the hot air is vented, and an awning shades the clerestory. Daylighting is diffused through translucent tubes to the spaces on the north side. (c) At the workroom, mirror-finish venetian blinds reflect direct solar radiation to the phase-change materials in bags above the dark metal deck ceiling. (Drawings* a *and* b *by Jonathan Meendering after original works by Banwell White Arnold Hemberger & Partners, Architects; photo* c *by C. Stuart White, Jr.)*

(*a*) (*b*)

HOW THIS BUILDING:

HELPS PLANTS TO GROW

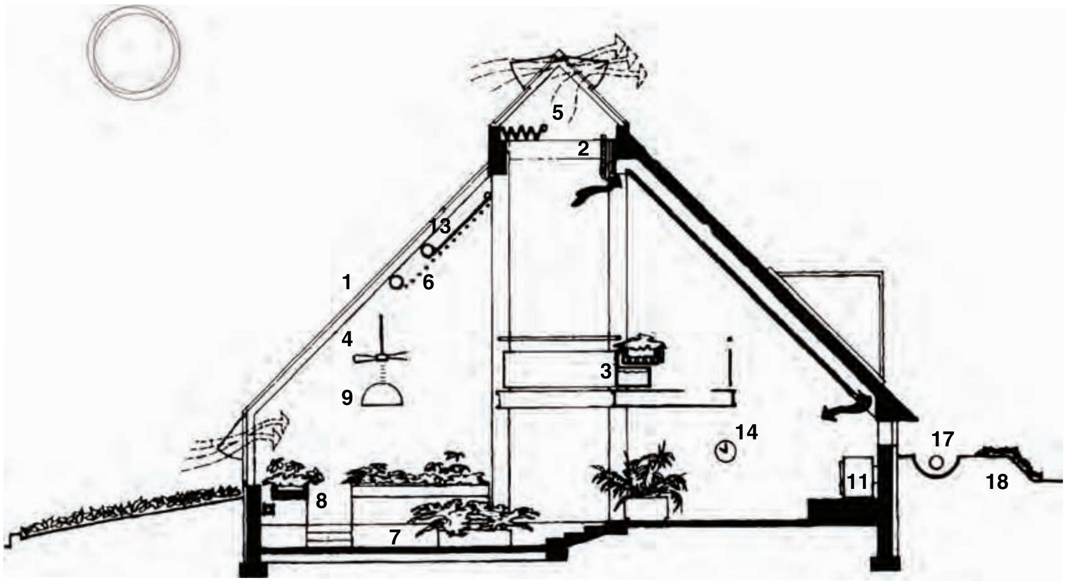
USES SOLAR HEATING (winter)

USES NATURAL COOLING (summer)

USES NATURAL LIGHTING

SAVES NON-RENEWABLE RESOURCES

1 South-facing greenhouse
2 Solar collectors
3 Thermal storage elements
4 Ceiling fans
5 Roof monitor
6 Operable sun-shade
7 Earth-contact floor
8 Root-bed heating
9 Grow-lights
10 Composting bins
11 Wood stove w/ heat recovery
12 Well-insulated structure
13 Operable insulating curtain
14 Automatic temperature controls
15 Energy efficient lighting
16 Water-saving plumbing
17 Roof-water collection
18 Earth-berms



(*c*)

Fig. 9.8 *The New Canaan (Connecticut) Nature Center (a, b) illustrates many passive and low-energy components. (c) Section illustrates the design features that utilize renewable energy and enhance energy conservation. The thermal storage elements are filled with eutectic salts that absorb excess solar heat via phase change (from solid to liquid) by day, then again change phase (from liquid to solid) at night to release their stored heat to the space. (Buchanan/Watson, Architects. Photo by Robert Perron. Courtesy of Donald Watson, FAIA, Troy, NY.)*

EXAMPLE 9.1 A small office building in Omaha, Nebraska, is to be passively solar heated. How much superwindow south glass area should be provided?

SOLUTION

Table G.1 shows that an Omaha building with a south glass area equal to 20% of its floor area can expect an SSF of 51 if its solar openings are superior performance.

Select 20% of the floor area for south glass: SSF = 51. Thermal mass can be estimated from Table G.2; for SSF = 50, either 30 lb of water or 150 lb of masonry (per square foot of south glass) should be provided. Using brick as a thermally massive surface, 3.7 ft^2 of brick should be provided for each square foot of south glass. ■

(e) Roof Ponds

This is yet another approach to passive solar heating, one not covered by the preceding guidelines. In general, roof ponds are used in warmer, less humid areas of the southern United States, where snow will not impede the movement of roof insulating panels, and the winter sun is higher in the sky than at northern latitudes. They are frequently sized for their *summer cooling* performance. In the U.S. southern latitudes, a pond sized for cooling will usually be adequate to absorb the needed winter sun. As a check for the pond's heating capacity, Mazria (1979) recommends the following guidelines:

Roof pond area = 85% to 100% of floor area for winter average outdoor temperatures of 25° to 35°F (−4° to +2°C)

Roof pond area = 60% to 90% of floor area for winter average outdoor temperatures of 35° to 45°F (2 to 7°C)

These guidelines are for roof ponds that have two layers of enclosing material between the water and the sky (i.e., are "double-glazed") and movable night insulation.

(f) Active Solar Heating

In contrast to passive systems, which incorporate sun collection and storage as part of a building's walls, floors, or ceilings, active solar heating uses mechanical equipment to collect and store solar energy. The most common early design questions for such systems involve the area of the solar collectors, their tilt and azimuth, and the size of the thermal storage.

For active solar space-heating systems, the guidelines are reasonably complex. Building heating needs vary by function and climate. The percentage of space heating that can economically be provided with active solar systems is another big variable. Nevertheless, a rough guide is desirable as a design starting point:

Collector/floor area ratio = the smaller of the two window/floor area ratios listed in Table G.1

This should provide a portion of the annual heating load somewhere in the range of high-performance SSF from Table G.1. Larger arrays of collectors can be designed, of course, but they rarely will be economically attractive.

For collector tilt and azimuth optima:

Optimum tilt = latitude plus 10° to 15°; optimum azimuth is from due south to 15° W of south

where the tilt angle is measured up from horizontal. An orientation somewhat west of south is attractive in climates with frequent morning fog. Also, because air temperatures are higher in the afternoon, collectors lose less heat then and therefore operate more efficiently.

The design guidelines for storage size are as follows:

2 gal of water storage per ft^2 (81 L per m^2) of collector

or

0.5 to 0.75 ft^3 of rock bed per ft^2 (0.15 to 0.23 m^3 per m^2) of collector

The large arrays of collectors necessary for space heating must be served by pipes or ducts. Whereas pipe size rarely influences design, air ducts for air-type collectors can consume large amounts of space. Therefore, the following flow rates are typical for active solar collectors:

water flow rate of 0.25 to 0.5 gpm per ft^2 (0.17 to 0.34 L/s per m^2) of collector

or

airflow rate of 2 cfm per ft^2 (10 L/s per m^2) of collector

Approximate pipe sizes can be determined from Chapter 19, and approximate duct sizing procedures are shown in Chapter 12.

9.4 CALCULATING WORST-HOURLY HEAT LOSS

We can obtain a building's total hourly heat loss in winter by determining heat transfer through a building envelope (q) and through ventilation of a building (q_v) (Chapter 7 showed how heat is exchanged). The total hourly heat loss of a building can be calculated under several different assumptions reflecting different purposes. Passive solar buildings attempt to minimize the use of conventional heating systems through the use of free solar heat. To understand that passive solar potential, we need to understand the amount of heat that a passive solar system replaces of a conventional heating system.

(a) Maximum Hourly Loss: Sizing Conventional Heating Equipment

The most typical use of $q + q_v$ is to determine the maximum amount of heat per hour that heating equipment must provide. Two important assumptions are usually made:

1. No internal heat gains (lights, people, etc.) and no solar gains are present in the building.
2. The *design* lowest outdoor temperature (see Appendix B) is occurring.

These are conservative assumptions that lead to the installation of heating equipment that is rarely used to capacity. Such equipment does provide a safety margin for those times when even lower than design temperatures occur or when windows are inadvertently left open or other temporary and unexpected heat leaks occur in very cold weather.

Thus, to obtain design hourly heat loss, calculate

$$q_{\text{total}} = q + q_v$$

where

$$q = (\Sigma UA)\Delta t$$

with ΣUA being the sum, for all exposed components of the building's envelope, of U × A; Δt = (interior temperature − exterior design temperature); and

$$q_v = 1.1\ V\ \Delta t\ (1.2 V\ \Delta t;\ \text{SI units})$$

where V is the volume in cfm (L/s) of outdoor air being introduced.

(b) Maximum Hourly Heat Loss: Sizing Auxiliary Heating for Passive Solar Buildings

The one important difference between the maximum heat loss calculations for conventional and passive solar buildings is the following assumption:

No internal heat gains (lights, people, etc.) are present, but there is sufficient stored solar energy to at least cancel out the heat losses through the south solar collection area.

Otherwise, the procedure is the same as that for conventional buildings:

$$q_{\text{total}} = q + q_v$$

where

$q = \Sigma\ UA_{ns}\ \Delta t$
q_v = 1.1 V Δt (Δt again based on the design condition, Appendix B) (1.2 V Δt; SI units)
$\Sigma\ UA_{ns}$ excludes the solar collector area

This can lead to occasionally chilly interiors, as when several days of heavily overcast skies coincide with design-condition outdoor temperatures. In some locations, therefore, designers use the more conservative, conventional procedure for sizing the auxiliary heating for passive solar buildings.

(c) Maximum Hourly Loss: Checking Design Criteria

The calculations that produce q and q_v are also useful in reviewing a building's design. By showing where most of the heat loss is occurring, they can quickly pinpoint opportunities for energy conservation and increased comfort. If much of the building's heat loss is occurring through large windows in one wall, for example, consider the following options:

1. Reduce the window size. (Architectural and daylighting considerations may override.)

2. Go to a lower window U-factor to reduce heat loss and increase the winter surface temperature of this large glass area. (Cost and detailing considerations may override.)
3. Add thermal shades or shutters to dramatically reduce heat loss and increase winter surface temperature. (Architectural, view, cost, and detailing considerations may override.)

If much of the building's heat loss occurs through outdoor air, consider these options:

1. Reduce infiltration by tighter construction (or reduce mechanical ventilation toward the code-required minimum).
2. Add a heat exchanger between outgoing and incoming air.

These calculations can also be used to check your building against published criteria for thermal performance (see Appendix I for example criteria). Redesign of building envelopes to meet such criteria is fairly common in the early stages of building design.

(d) Hourly Rates of Fuel Consumption

When outdoor temperatures in winter drop below the building balance point (see Section 9.5), heating systems usually begin to operate. The hourly rate of fuel consumption depends on the hourly heat loss from the building. If the boiler (or furnace) is selected to run continuously at the outdoor, critical winter design temperature, then it will cycle (run intermittently) at higher outdoor temperatures. The equipment, however, *is* selected on the basis of the maximum winter demand load and therefore relates to the calculated heat loss at the design temperature. Sometimes your energy supplier will ask for the maximum hourly rate.

EXAMPLE 9.2 Calculate the rates of burning for several fuels (or the rate of using electricity) to make up the hourly heat loss, under design conditions, of a mercantile store. Its maximum hourly heat loss is 159,840 Btu/h. For fuel values, refer to the data in Table 9.2.

SOLUTION

If, for instance, oil were used, the situation would be gal/h × Btu/gal heat value × efficiency = Btu/h capacity (= heat loss). Transposing, we have

TABLE 9.2 Approximate Heat Values of Fuels

	Heat Value		Typical
Fuel	I-P Units	SI Units	Seasonal Efficiency, %
Anthracite coal	14,600 Btu/lb	33,980 kJ/kg	65–75
No. 2 oil	141,000 Btu/gal	39,300 kJ/L	75–90[c]
Natural gas[a]	1,050 Btu/ft^3	39,100 kJ/m^3	75–95[c]
Propane	2,500 Btu/ft^3	93,150 kJ/m^3	75–95[c]
Electricity	3,413 Btu/kW	1 kW	95–100
Wood[b]	7,000 Btu/lb	16,290 kJ/kg	30–50

Note: This table includes the thermal value of electricity used on site (but not losses in fuel energy at the electrical generating plant). Approximate seasonal efficiencies of typical burner–boiler equipment are also shown.

[a]Natural gas is frequently sold in therms; 1 therm = 100,000 Btu/h (SI units, 29.3 kW).

[b]At 20% moisture content.

[c]Depending upon age of equipment; high-efficiency furnaces are readily available.

$$\text{gal/h} = \frac{\text{Btu/h heat loss}}{\text{Btu/gal} \times \text{efficiency}}$$

(Other consumption statements are similar.) Applying values to this and to relationships for the other fuels, using I-P units we obtain the following rates:

Coal: 159,840/14,600 × 0.70 = 15.6 lb/h

Oil: 159,840/141,000 × 0.75 = 1.51 gal/h

Gas (older, less-efficient equipment): 159,840/1052 × 0.75 = 203 cfh

Electricity: 159,840/3413 × 1.00 = 46.6 kW

These results are based on the assumption that the boiler and its piping are enclosed within the useful volume of the store. If they were in a cold basement, or if the ducts or pipes ran through unheated space, more fuel would be used, and overall system efficiency would decline. The rates established set the values by which the fuel-burning apparatus is selected. For instance, if oil is used, a nozzle that injects oil at the rate of about 1 gph should be tried. These rates are for design conditions and are not typical of the lower average rate of operation throughout the winter. ■

9.5 CALCULATIONS FOR HEATING-SEASON FUEL CONSUMPTION (CONVENTIONAL BUILDINGS)

The following method of estimating the fuel used for space heating in a typical season best applies to residences and small commercial buildings that are skin-load dominated and not passively solar heated beyond SSF = 10%. To the extent that the combination of internal and solar gains can be predicted accurately, this method yields a reasonable estimate of annual fuel consumption for any building.

Internal and solar gains make almost any building warmer than the outdoors during the heating season. The furnace (or other space-heating device) is not needed until the outdoor temperature drops to the point at which these internal and solar gains are insufficient to heat the building by themselves, that is, when the heat lost through the building's skin and infiltration matches the heat gained through solar plus internal loads. This particular outdoor temperature is called the *balance point*; it represents the beginning of the need for space-heating equipment.

To estimate the annual energy needed for a building's space heating, it is necessary to know the following:

- The building's heat-loss rate (envelope and infiltration)
- The building's internal plus solar gain rate
- The building's balance point temperature
- The extent of time during which the outside temperature falls below the building's balance point temperature (DD)

(a) Balance Point Temperature

When a building needs neither heating nor cooling, the internal gains equal the external losses:

$$Q_i = \text{balance point } q_{\text{total}}$$

where

Q_i = internal gains plus solar gains (Btu/h or W)

balance point $q_{\text{total}} = UA_{\text{total}}\,(t_i - t_b)$

t_b = balance point temperature

t_i = average interior temperature over 24 hours, winter

UA_{total} = total heat loss rate envelope plus infiltration; in (Btu/h °F or W/°C)

Rewriting this equation to solve for the balance point temperature:

$$t_b = t_i - \frac{Q_i}{UA_{\text{total}}}$$

To determine the total heat loss rate UA_{total}, combine the envelope (or skin) losses and the infiltration (or ventilation) losses.

The quantity Q_i cannot be determined so straightforwardly. The internal gains can be estimated as shown in Table G.3 (remember, these are summertime gains) or calculated more precisely from known building population, lighting, and equipment data. For residences, the following *daily total* internal gains are considered typical:

People: Two adults and two children (average times of occupancy): 23,000 to 24,500 Btu/day (6.7 to 7.2 kWh/day)

Lights and equipment: See Table 9.3 for individual heat sources, but if actual appliances are unknown, then:

53,000 Btu/day (15.5 kWh/day) for standard-efficiency equipment

100,000 Btu/day (29.3 kWh/day) for old and inefficient equipment

TABLE 9.3 Typical Residential Daily Internal Heat Gains from Appliances and Lighting

PART A. ELECTRIC APPLIANCES		
Heat Source	**Btu/day**	**kWh/day**
Frost-free refrigerator	16,000	4.7
Freezer	10,900–15,700	3.2–4.6
Dryer[a]	8,900–11,600	2.6–3.4
Range[a]	6,500–11,300	1.9–3.3
Television[b]	3,400–4,400	1.0–1.3
Dishwasher	2,400	0.7
Lighting and miscellaneous[c]	9,500–18,800	2.8–5.5
Water heater[d]	13,700–27,400	4.0–8.0
PART B. GAS APPLIANCES		
Heat Source	**Btu/day**	
Water heater	13,700–27,400	
Dryer[a]	12,000–19,000	
Range[a]	12,000–27,000	

Source: A New Prosperity: Building a Sustainable Energy Future, The SERI Solar Conservation Study. Brick House Publishing. Andover, MA, 1981. Previously adapted, with the permission of ASHRAE, from the *1989 ASHRAE Handbook—Fundamentals.* This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

[a]These are for the appliance's consumption per day; heat gain to a house is less, depending on the amount of heated exhaust air.

[b]Total daily use of TV per household.

[c]These figures are for an average 1350-ft^2 house; the rate per square foot of floor area may be extrapolated.

[d]Standby heat loss from water heater to house.

For more details on internal gains in residences, see the 2013 *ASHRAE Handbook—Fundamentals*, Chapter 17.

The solar gains are elusive; each month has a different average gain. For simplicity, in the heating season, use the average January daily insolation on a vertical surface (found in Appendix C) with this approach.

During the heating season:

$$Q_i = \frac{\text{internal gains (Btu/day)}}{24\text{ h}} + \frac{\left[\begin{array}{l}\text{January insolation} \\ \text{(Btu/ft}^2\text{ day average),} \\ \text{vertical surface}\end{array} \times \begin{array}{l}\text{area (ft}^2\text{),} \\ \text{south glass}\end{array}\right]}{24\text{ h}}$$

The balance point temperature, t_b, can be used to do several things besides predict fuel consumption. By noting the t_b on a graph of monthly outdoor temperatures, the designer can quickly see the relative importance of heating versus cooling for a specific building in a given climate. Also, it can be used to gain a better understanding of how zones in a building interrelate. Once the t_b is calculated for each zone, the designer can determine when the entire building needs heating (outdoor temperature below any zone's t_b) or cooling (outdoor temperature above any zone's t_b), or when one zone's surplus heat can be another zone's space-heating source (outdoor temperature higher than one zone's t_b but lower than that of another). If thermal exchange between zones occurs for a major portion of the typical year, the choice of either a heating or a cooling strategy could be influenced.

(b) Degree Days (DD)

These data (found in Appendices B, C, and G) are published for each climate station and are calculated to various *base* temperatures. Heating degree days (HDDs) to a specified base temperature, such as HDD65, refer to average daily temperatures *below* the base temperature of 65°F. Cooling degree days (CDDs) to a specified base temperature, such as CDD50, refer to average daily temperatures *above* the base temperature (of, say, 50°F). (Climate data previously showed cooling degree hours [CDH], such as CDH74, referenced to the average number of hours above a base temperature of 74°F. These data appear to have been generally displaced by CDD data.) For smaller buildings, such as residences, HDDs are in much wider usage than are CDDs (or CDHs), and many data sources simply list DD65; this notation is interchangeable with HDD65. Until recently, degree days were always based on 65°F, because older, indifferently insulated buildings, with low internal gains, had a typical balance point of about 65°F. The combination of much higher levels of insulation and much more electric equipment has shoved the average building's balance point temperature downward; hence DD50, DD55, and DD60 are included with the traditional DD65 in Appendix C.

To derive HDD for a particular climate and *X* base temperature (HDD*X*), each day's mean temperature (halfway between high and low) is subtracted from the base temperature; the result is the number of HDD*X* for that day. If the mean temperature equals or exceeds the base temperature, no HDD are recorded. Then the HDD*X* are totaled for an average year.

TABLE 9.4 Some Typical Values of Annual Fuel Utilization Efficiency (AFUE)

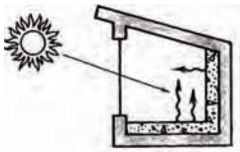
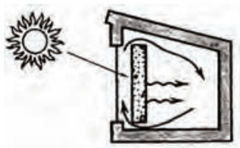
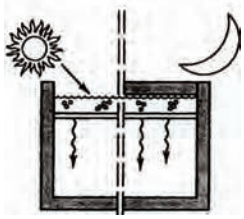
	AFUE (%)	
Type of Furnace	**Indoor**	**ICS[a]**
NATURAL GAS		
Natural draft with standing pilot[b]	64.5	63.9
Natural draft with intermittent ignition[b]	69.0	68.5
Natural draft with intermittent ignition and auto vent damper[b]	78.0	68.5
Fan-assisted combustion with standing pilot or intermittent ignition	80.0	78.0
Fan-assisted combustion with improved heat transfer, with standing pilot or intermittent ignition	82.0	80.0
Direct vent with standing pilot, preheat[b]	66.0	64.5
Direct vent, fan-assisted combustion, and intermittent ignition	80.0	78.0
Fan-assisted combustion (induced draft)	80.0	78.0
Condensing	90.0	88.0
OIL		
Standard[b]	80.0	78.0
Standard with improved heat transfer[b]	81.0	79.0
Standard, with improved heat transfer and auto vent damper[b]	82.0	80.0
Condensing	91.0	89.0

Source: Reprinted with permission; ©ASHRAE, 2012 *ASHRAE Handbook—HVAC Systems and Equipment.*

[a]Isolated combustion system: combustion air is drawn from outdoors, not indoors.

[b]Since 1992, all new furnaces are required to have an AFUE (ICS) level of at least 78.0%.

TABLE 9.5 Passive Solar Heating Systems

	Influence on Plan	Heating Characteristics
Direct gain (DG) 	Sun can enter through south windows or skylights; open plan can allow sun and stored heat to serve entire top floor of building. Large areas of thermal mass surface should be darker-colored and free of rugs, wall hangings, etc. Light-colored surfaces near glass reduce glare. Outdoor view and access to south are encouraged.	Quick to warm up in the morning; fast response to sun. Tendency to overheat at midday; large temperature swings. Much radiant loss to bare window by night; movable insulation encouraged (or triple glazing or selective film). Warmth spread throughout space along with thermal mass.
Thermal storage wall Trombe (masonry) wall (TW) Water wall (WW) 	Needs to be on south wall of building. Inner wall of TW or WW should be kept clear of hangings, furniture, etc., but rest of space is unrestricted. Not much solar impact beyond about 25 ft from TW or WW. Outdoor view and access to south are discouraged.	Unvented TW, WW are slow to warm up by day, slow to cool by night; small temperature swings. Most radiant heat arrives in evening; comfort is most likely near the TW or WW surface. (Behavior of vented TW is midway between those of unvented TW and DG systems.)
Sunspace (SS) 	Same influences as TW and WW just described; or SS can be insulated from building, becoming a less-efficient heat source for a rock bed. Floor above rock bed should be kept free of rugs. SS becomes a special place with different characteristics from rest of building. Access to SS thereby encouraged. Access to south encouraged; view to south filtered.	SS thermally like DG, but with extreme temperature swings and accentuated radiant loss by night. Movable insulation often omitted and night use curtailed. Building beyond is thermally like TW or WW, depending on its connection with SS. Warm floor above rock bed in months with SS surplus heat.
Roof pond 	Flat or nearly flat roof is desirable. Skylight is discouraged. Plan is completely unrestricted; sidelighting and views, access to outdoors encouraged.	Low-temperature swings; steady temperatures in both summer and winter. Winter air stratification possible, since warmest surface is also highest surface in the space.

For example, assume that a day in Troy, New York, had a high of 60°F and a low of 34°F. The mean temperature was $(60 - 34/2) + 34 = 47°F$.

$$65 - 47 = 18\ \text{DD65}$$
$$60 - 47 = 13\ \text{DD60}$$
$$55 - 47 = 8\ \text{DD55}$$
$$50 - 47 = 3\ \text{DD50}$$

Clearly, a building with a 65°F balance point will need more heat on a given day than will a building with a 50°F balance point temperature.

To convert DD I-P to DD SI, simply multiply DD I-P by 0.56:

$$\text{DD SI} = 0.56\ \text{DD I-P}$$

To obtain the *DD balance point* needed to estimate a particular building's heating needs, interpolate

TABLE 9.5 Passive Solar Heating Systems (*continued*)

	Daylighting	Cooling
DG	Very high daylight factor (DF) possible, with high glare potential at lower windows. Possible conflict between light-colored surfaces for glare reduction and dark-colored surfaces for solar absorption. Summer shading greatly reduces DF. Encourages both side- and toplighting.	Cross-ventilation: encouraged by large windows to south. Stack ventilation: helped when clerestories are used. Night ventilation/thermal mass: excellent potential, much mass surface and capacity. Other closed-building cooling: large south windows are big threat. Shading (and lower DF) necessary in overheating months.
TW, WW	No daylighting through TW unless interrupted by windows (high glare potential). Diffuse light possible through translucent WW. Discourages sidelighting.	Cross-ventilation: discouraged by solid TW, WW. Stack ventilation: TW or WW can itself produce a stack effect, but with risk of evening overheating. Night ventilation/thermal mass: limited interior mass surface exposure but a lot of mass capacity. Other closed-building cooling: with summer shading of TW or WW, good match with controlled cooling; thermal mass delays and reduces peak heat gains.
SS	Very high DF within SS; little or no daylight through common wall, except as encouraged by view and access to surface. Summer shading of SS reduces DF.	Cross-ventilation: only to extent that common wall is penetrated for view and access. Stack ventilation: SS can become a moderately effective stack. Night ventilation/thermal mass: both surfaces of common mass wall are available, but two spaces must be cooled. Other closed-building cooling: with summer shading of SS, good match with controlled cooling (except in SS itself).
Roof pond	Discourages toplighting, encourages sidelighting, with very light color on underside of roof.	Cross-ventilation: excellent potential. Stack ventilation: discouraged. Night ventilation/thermal mass: easily achieved with roof undersurface. Other closed-building cooling: roof pond night sky cooling is often sufficient by itself, making other cooling unnecessary.

Source: Illustrations from AIA: Ramsey/Sleeper, *Architectural Graphic Standards*, 11th ed., © 2007 John Wiley & Sons, Inc., Hoboken, NJ. Reprinted by permission.

between the various base DDs as required. (If the balance point is below 50°F, get lower DD base figures from your local weather station. Do not extrapolate!)

(c) Yearly Space-Heating Energy

To estimate the heating fuel energy, E, needed over an average year for a building, calculate

$$E = \frac{(UA)(\text{DD balance point})(24\text{ h})}{(AFUE)(V)}$$

where

E is in units of fuel consumed per year (therms of gas or kWh of electricity)

UA is the total heat loss rate, envelope + infiltration (Btu/h °F, or W/°C)

DD is balance point, obtained as just described

AFUE is the annual fuel utilization efficiency, displayed on all furnaces manufactured within the United States (Table 9.4)

V is the heating value of the fuel from Table 9.2

EXAMPLE 9.3 A residence in Springfield, Illinois, has a total heat loss rate UA of 544 Btu/h °F and a balance point temperature of 55°F. It will have a natural gas condensing furnace, located indoors, for which AFUE = 0.93. For Springfield, DD55 = 3434. The approximate average annual energy used for space heating is

$$E = \frac{(544\ \text{Btu/h °F})(3434\ \text{DD})(24\ \text{h/day})}{0.93 \times 100{,}000\ \text{Btu/therm}}$$
$$= 482\ \text{therms}$$ ■

9.6 DETAILED CALCULATIONS: PASSIVE HEATING PERFORMANCE

Earlier in this chapter, design guidelines were given for determining solar opening size, thermal mass, and the solar savings fraction (SSF). As a building design takes shape, more detailed information becomes useful: Which passive system matches the architectural program? Which performs better thermally? For a given solar opening, what exactly is the resulting SSF? How much auxiliary fuel consumption per year must accompany that SSF? If a building overheats on sunny winter days, how hot will it get?

To this point, passive solar heating has been treated as a single approach; the design guidelines for SSF distinguished only between standard and superior system performance. Important architectural differences, however, characterize the various passive solar heating approaches, as summarized in Table 9.5. On the basis of the wider architectural implications presented in Table 9.5 and the detailed sizing information found in Appendix I, the designer can select a passive solar heating approach with some confidence in its applicability and its yearly need for auxiliary space heating. This section provides examples that recognize the need for more detailed sizing information for some of the solar heating strategies.

(a) Glazing Performance

In the reference systems of Table I.1, the glazing is assumed to face due south. The choices of glazing conditions include single, double, and triple glazing, and night insulation "no" or "yes." Single, double, and triple glazing with no night insulation are common approaches. Movable night insulation, once common (Fig. 9.9), has largely been supplanted by superwindows. Yet, which of the current superwindows might provide a performance approximately equivalent to double glazing with R-9 night insulation?

The 24-hour averaged U-factor of the double-glazed fixed window with R-9 night insulation is found as follows: A double-glazed window, with a wood/vinyl frame, corresponds to window #5 in Table E.15, with U = 0.49. "Night insulation" assumes adding R-9 insulation, in place from 5:30 P.M. to 7:30 A.M. This extra-insulated window should at night then have an overall R of at least

$$(1/0.49) + 9 = \text{R-11}$$

then nighttime $U = 1/11 = 0.09$.

$$U_{24\text{av}} = \left[\frac{(14\ \text{h})(0.09)] + [(10\ \text{h})(.49)}{24\ \text{h}}\right] = 0.257$$

The equivalent superwindow would then have these characteristics, based on window #5's solar gain:

$$\text{U} = 0.26,\ \text{SHGC} = 0.58,\ \text{VT} = 0.57$$

Such a combination may be difficult to obtain. Here are some choices for superwindow substitutes for the "double/yes n.i." option within the Appendix I reference types:

- Where listed, choose the triple-glazing option instead of the double/yes n.i.
- Use window #7, Table E.15, with U = 0.33, SHGC = 0.55, VT = 0.52, with nearly identical

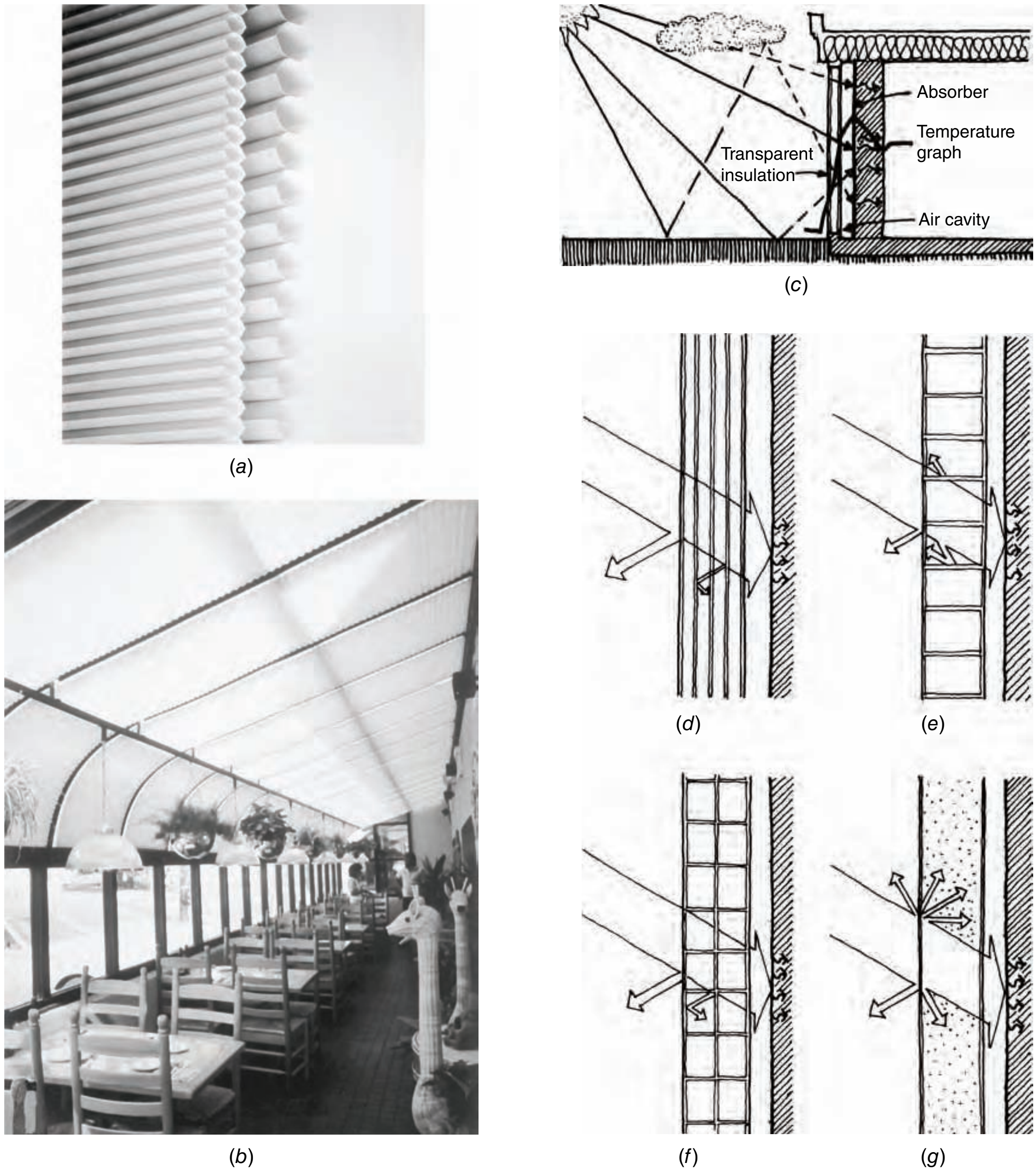


Fig. 9.9 *Variations on insulation for solar apertures. Transparent insulation materials (TIMs) in most applications are more translucent than transparent. (a) The Duette window shade, when installed over double glazing, has winter R-values as follows: at ⅜ in. (9.5 mm) thick: translucent, R 3.23; ¾ in. (19 mm) thick: translucent R 3.57; opaque, R 4.2. (b) The shades can move either vertically or horizontally, cover both planar and curved surfaces, and be either motor or manually operated. (c) These translucent materials are particularly effective as insulation for Trombe walls, where the heated mass can be insulated from the cold winter air temperatures yet still receive strong sunlight. (Courtesy of the Fraunhofer Institute, Freiburg, Germany, and* Solar Today, *American Solar Energy Society.) (d) Absorber-parallel systems utilize multiple films, as in "superwindows." The more layers, the greater the optical losses. (e) Absorber-vertical structures include honeycomb or capillary materials. Some scattering and absorption of light occurs, but optical losses are lower than with type (d). (f) Cavity structures combine absorber-parallel and absorber-vertical structures. (g) Quasi-homogeneous layers are similar to cavity structures and include aerogel. (Courtesy of Hunter Douglas, Inc., Broomfield, CO.)*

solar gain characteristics, and interpolate between double/yes n.i. and double/no n.i. on the basis of U-factors:

Double/no n.i., U = 0.49
Double/yes n.i., U = 0.26
Window #7, U = 0.33

This places window #7 at about one-third of the difference, closer to double/yes n.i.

- Use the clear triple-glazed window (#12, Table E.15) in place of double/yes n.i., and given its U = 0.34, SHGC = 0.52, VT = 0.53, interpolate for U-factor as with window #7.

Another option is *transparent insulation materials* (TIM), such as aerogel (one example). These materials transmit diffuse light and solar radiation but are opaque to infrared radiation. The four generic types of TIM are shown in Fig. 9.9. The absorber-parallel structures (Fig. 9.9*a*) are similar to the sheets of spectrally selective materials in superwindows; the more layers, however, the less the transmission of solar gain. Absorber-vertical structures (Fig. 9.9*b*) include honeycomb or capillary materials that reflect and transmit the incoming solar radiation with fewer transmission losses. Combining these structures (Fig. 9.9*c*) can result in either transparent rectangular cross sections or transparent foam with bubble sizes of a few millimeters. Quasi-homogeneous layers (Fig. 9.9*g*) include aerogel. These scatter the incoming solar radiation differently than do the types of structures shown in Fig. 9.9*c*.

For passive space heating, TIM use may be limited by the lack of *visual* transparency: These materials diffuse sunlight. They are thus appealing primarily for Trombe wall and water wall applications (Fig. 9.9*e*), where the view through the glazing is unimportant. Some information on U-factors and diffuse transmittance is presented in Table 9.6. Again, if we seek a substitute for movable insulation over double glazing, we would like U = 0.26, SHGC = 0.58, VT = 0.57; from Table 9.6, any of the honeycomb or capillary materials in Part A will be close if we remember to reduce the τ diffuse and slightly increase the U-factor to account for a single cover sheet of glass.

TABLE 9.6 Transparent Insulation Materials (TIM)

PART A. HONEYCOMB AND CAPILLARY STRUCTURES			
		U-Factors[a,b]	
TIM	**τ Diffuse**[b]	**Btu/h ft² °F**	**W/m² K**
Honeycomb polycarbonate			
Thickness 1.97 in. (50 mm)	0.85	0.35	2.0
Thickness 3.94 in. (100 mm)	0.78	0.19	1.07
Capillaries, polycarbonate			
Thickness 3.94 in. (100 mm)	0.73	0.17	0.98
Capillaries, PMMA (acrylic glass)			
Thickness 3.94 in. (100 mm)	0.80	0.16	0.91
PART B. AEROGEL BETWEEN DOUBLE GLAZING			
		U-Factors[a]	
Aerogel Granule Diameter	**τ Diffuse**[b]	**Btu/h ft² °F**	**W/m² K**
<0.079 in. (<2 mm)	0.22	0.17	0.98
0.118–0.157 in. (3–4 mm)	0.40	0.18	1.03
0.157–0.236 in. (4–6 mm)	0.42	0.20	1.13
0.236–0.315 in. (6–8 mm)	0.43	0.20	1.15

Source: Wittwer et al. (1991).
[a]Mean temperature 50°F (10°C), Δt 18F° (10 K).
[b]Part A values are based on the TIM only, without the glass cover necessary in the actual application.

(b) Direct-Gain (DG) Systems

These are the most commonly encountered systems because nearly all south-facing spaces have windows, and at least some have areas of internal thermal mass. In Table G.4, three of the four early solar examples utilize some DG collection. The most common problems are overheating on sunny winter days and inadequate area of thermal mass.

For DG spaces, the thermal mass should be widely distributed around the room so that direct solar radiation can strike the mass surface and/or be reflected to the mass surface as soon as possible on entering the window. Table G.2 gives design guidelines for mass; the DG reference systems (Appendix I) list either a 3:1 or a 6:1 mass-to-glass area ratio. However, even more mass area will give a more thermally stable performance, as will become clear in Section 9.6(h); a common recommendation for DG spaces above 50% SSF is for a thermal mass area five to seven times the area of glass (for no more than the optimum 4-in. masonry thickness). There are many common ways to provide such mass surfaces, including brick veneer and clay tile over a bed of grout. These surfaces can be applied to a frame construction. Floors (such as slab on grade) are easy ways to achieve large mass areas, but carpeting and rugs are very popular with occupants.

(c) Sunspaces (SS)

These are the next most common systems, especially the prefabricated “add-on” type shown in the Kelbaugh house (Table G.4). Perhaps the most common problem is the expectation that an SS will be a greenhouse where exotic plants will thrive. But the SS is the collection area (essentially the “boiler room”) that serves the rest of the living space; comfortable temperatures in the living space are achieved by *very wide temperature swings* in the SS. Consequently, while there are many times in a day when the SS is at a comfortable temperature, there are other times when it is not. In the First Village example (Table G.4 and Fig. 9.10), the SS contains the stairs. Although not always thermally comfortable, the passage between floors is at least rapid and visually pleasant. The living spaces beyond, on both floors, can choose the degree of interaction with the SS by opening doors and windows into it.

When the SS’s common wall is masonry, the conductive flow of heat from SS to the living space is built in. Yet many of the SS systems in Appendix I show an insulated, lightweight-frame common wall. It is important to remember that, with such insulated common walls, the SS is assumed to contain *a row of water containers* extending across the full east–west width of the SS. These theoretical containers are twice as high as they are wide and sit adjacent to (but not on) the floor and the common wall. They have a volume of 1 ft^3 for every 1 ft^2 of common wall. This takes quite a bit of SS floor area.

Both masonry and insulated common wall SS systems assume available thermocirculation vents in the common wall; the top vents are 8 ft (2.4 m) above the bottom vents, and the top vents constitute 3% of the area of the common wall, as do the bottom vents. All SS systems are assumed to have a thermally massive, perimeter-insulated slab on grade floor.

The SS system descriptions are quite explicit as to dimensions (Fig. I.1), but variations from these dimensions are not a problem *if the proportions of length-width-height are maintained*. It is the shape, rather than the dimensions, of each SS type that influences its performance.

(d) Trombe Walls (TW)

These systems are considerably less common. When used, they often have rather large DG openings within the TW for daylight and view. This is the case with the Kelbaugh house (Table G.4), an unusual example that mixes three passive systems. The main advantage of TW systems is thermal stability; the diurnal temperature swings are less than with most other passive systems. They deliver a large portion of their heat by radiation to the space. The main disadvantages seem to be the loss of view and daylight, and keeping the air space clean between the Trombe mass wall and the glass. Objects that interfere with radiant heat transfer from the interior surface must also be minimized.

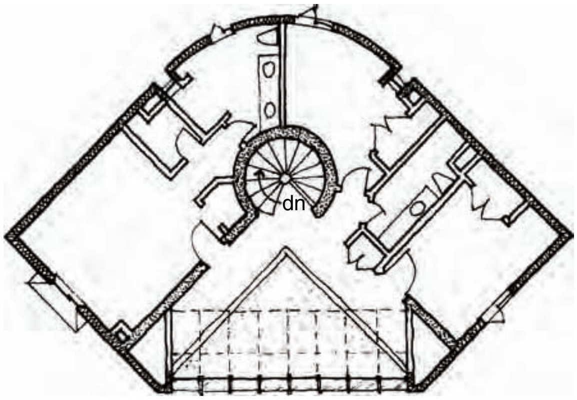
Two major choices are *vented* and *unvented*. The vented TW systems provide naturally moving air (via the stack effect between the mass and the glass) in addition to heat conducted through the mass wall. They deliver warmer air sooner than an identical-but-unvented mass wall, thanks to the flow of warmed air. They also introduce dust and dirt to the space between the mass and the glass.

The unvented TW systems deliver heat quite a bit later, with the result of quite low daily temperature variations and warmth arriving in the evening. They are somewhat less efficient than vented TW because the very high temperature at midday between the mass and glass results in more heat flow out through the glass.

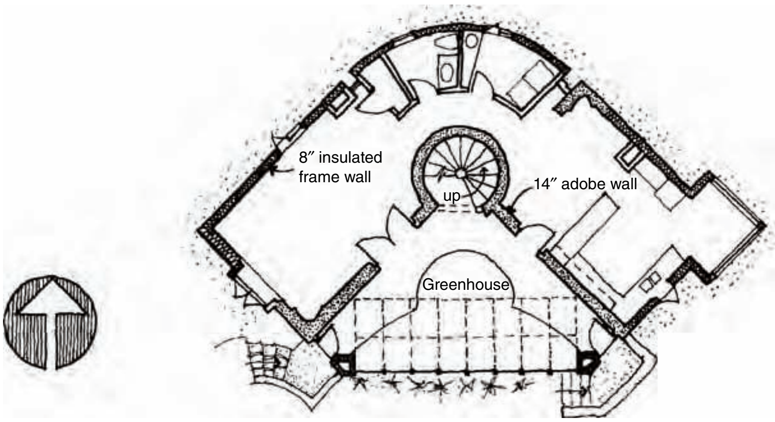
The warehouse in Fig. 9.11 utilizes a very high vented TW in the New England winter. The detail shows a simple device to prevent reverse airflow at night. This Vermont warehouse utilizes ceiling fans to prevent stratification of warm air at the ceiling. Daylighting is provided by roof monitors; the TW is vented to the outside in summer.

(e) Water Walls (WW)

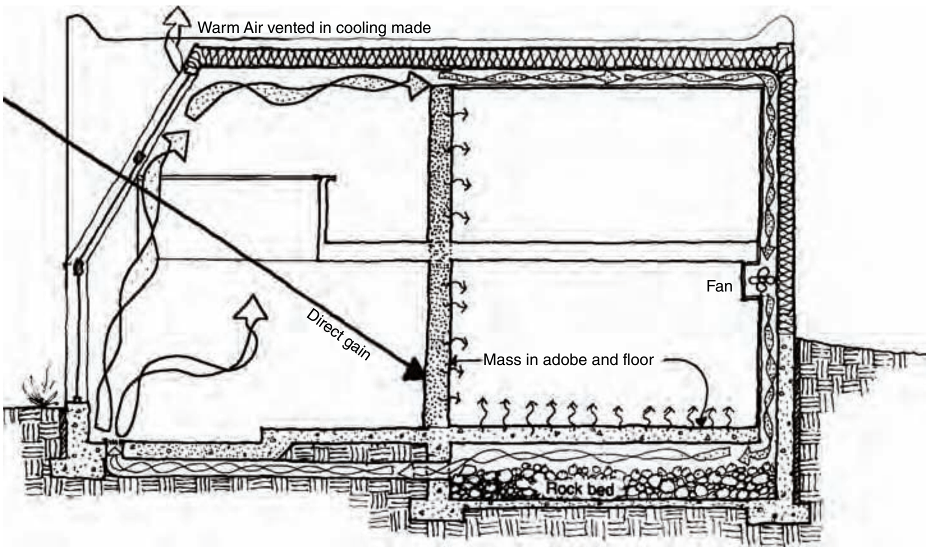
The least common system is the water wall. Perhaps, as with roof ponds, this is another case of



(*a*) Second floor plan



(*b*) Ground floor plan

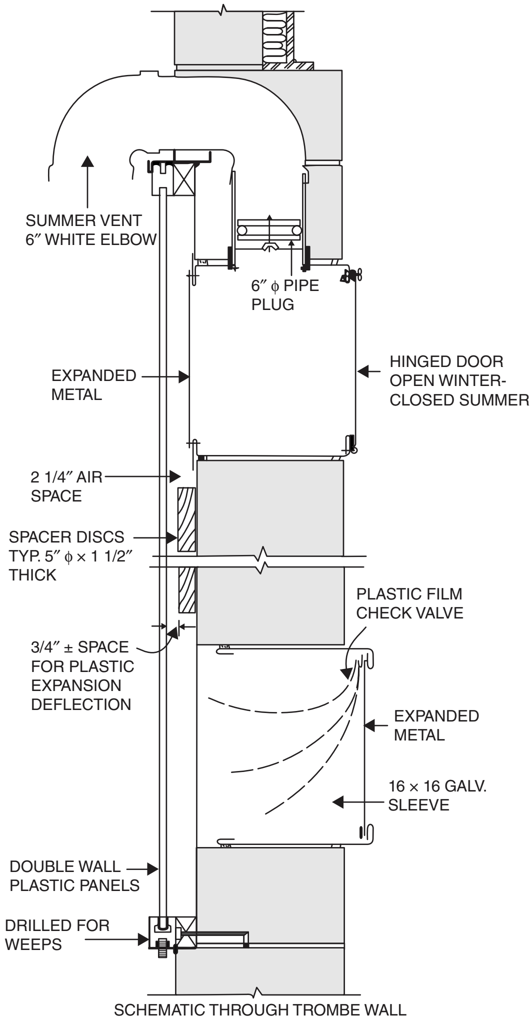


(*c*) Section

Fig. 9.10 *An early and well-known example of sunspace passive solar heating, Unit 1, First Village. Regularly occupied spaces border the northeast and northwest sides of the enclosed sunspace. (a) Upper floor plan. (b) Ground floor plan. (c) Section showing how the hottest air from the sunspace (midday to late afternoon) can be forced into a rock bed below the main floor for nighttime radiant heat. (Drawings based in part on Sandia National Laboratory, 1977.* Passive Solar Buildings: A Compilation of Data and Results*. Sand 77-1204.)*

(*a*)

(*b*)



(*c*)

Fig. 9.11 *The warehouse for the Famolare shoe company in Brattleboro, Vermont (a) uses a huge vented Trombe wall, 20 ft by 184 ft (6.1 m by 56.1 m). The Trombe wall faces 10° east of south. The pond in the foreground is an absorption basin for rainwater from the roof and pavement. (Photo by Robert Perron.) (b) Interior shows lower and upper vents. (c) Simple switches at the bottom prevent reverse thermosiphoning on cold nights; seasonal switches at the top provide building ventilation, via the Trombe wall, in summer. Spacer disks prevent plastic double glazing from deflecting too far inward when its inner surface overheats. (Reprinted from* Architectural Record*, November 1979; © 1979 by McGraw-Hill, Inc.; all rights reserved. Reproduced with the permission of the publisher. Courtesy of Banwell White Arnold Hemberger & Partners, Architects, Hanover, NH.)*

water phobia. Water containers can be specially made, or made of corrugated galvanized steel culverts, steel drums, or fiberglass-reinforced plastic tubes (for which manufacturers provide suggested installation details). Within WW containers, some air space should be provided, because water expands when it heats. Either a rust inhibitor or a sacrificial anode should be added to the water within steel containers. Specially made containers can fit neatly below windows or anywhere else within exterior wall framing. With that approach, buildings can utilize windows for daylight and controlled DG.

The San Luis Solar Group Complex includes a house and an architectural studio (Fig. 9.12) near Santa Margarita, California. Both buildings utilize daylight (including clerestories and skylights), DG, PV, and domestic water panel collectors; there is also a small hydropower system adjacent to the complex. Of special interest here are the WW steel panels, 9 in. (230 mm) thick and painted on the outer surface with a black selective paint behind double glazing. The selective surface paint is an excellent absorber of short-wave solar radiation but a poor emitter of long-wave radiation from the heated black surface. The inside steel surface is painted and exposed to the space to be heated. These WW are used in the conference room of the studio, the dining area, and the upstairs bedroom. They are unobtrusive and correspond approximately to WWC2 in Appendix I.

Most WW systems should be opaque, not transparent; the more transparent the tubes, the closer to DG will be their performance. An example of a transparent WW was developed by the University of Arizona 2009 Solar Decathlon team, called the *SEED [pod]* house (Fig. 9.13), To reduce heating and cooling needs, the team designed a vacuum-formed clear plastic water wall to fit within the south wall. The wall is intended to function as a "heat sink" by absorbing heat during the day and releasing it slowly after the sun goes down. In addition, the WW allows adequate daylight into the space.

(f) Load Collector Ratio (LCR) Annual Performance

The following procedure is based on Balcomb et al., *Passive Solar Heating Analysis* (1984), published by ASHRAE and reprinted by permission. The reference offers a much wider variety of passive systems and a wider network of location listings than can be presented in this book. Along with numerous "sensitivity curves" to allow prediction for nonstandard passive systems, the reference also provides a much more time-consuming and detailed method for calculating the *monthly* SSF and auxiliary energy needs; the method presented here gives annual results only. Thus, Balcomb et al. (1984) is an important and perhaps indispensable reference for the serious passive solar designer.

The method presented here, called the *load collector ratio* (LCR), yields the annual SSF and auxiliary energy needs for a building. This method has the following steps:

STEP 1. Choose the location and the reference passive system that most closely coincide with your building and its site. The locations listed in Appendices C and I are shown in Fig. C.1; the reference passive systems for which performance data are available (Appendix I) are summarized in Table I.1. If your system differs significantly from the closest reference system, see Section 9.6(g).

STEP 2. Tentatively select a size for the solar openings, balancing the design guidelines for SSF (Table G.1) with those for daylighting (Chapter 8) and, if applicable, for ventilation.

STEP 3. Calculate the "non-south" envelope heat loss rate, UA_{ns}, for the building design—one that *excludes* the solar openings but *includes* all other envelope losses, as well as the infiltration loss. Then multiply UA_{ns} by 24 h to obtain Btu/DD; this is called the *building load coefficient* (BLC).

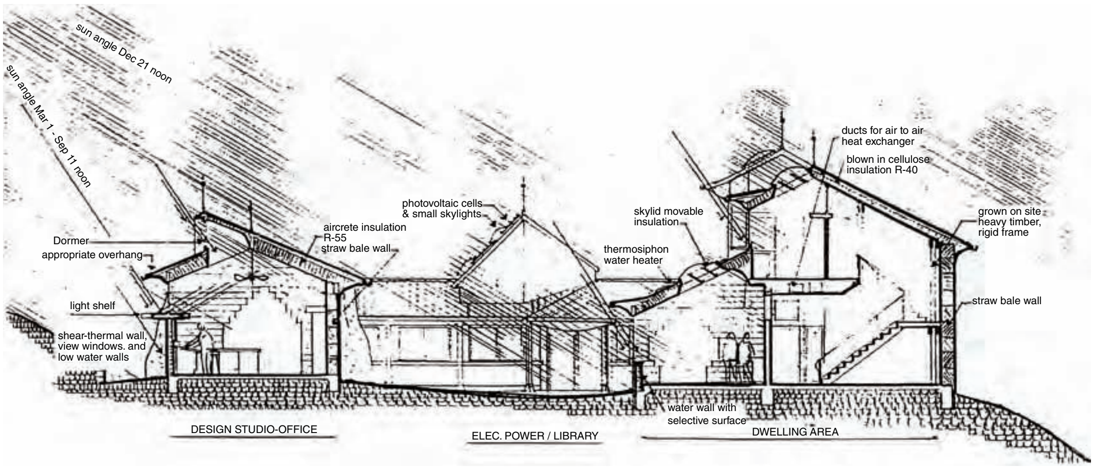
$$\text{BLC} = 24 \times UA_{ns}$$

STEP 4. Check your building's overall loss rate against the criteria from Table 9.1:

$$\text{Btu/DD ft}^2 = \frac{\text{BLC}}{\text{floor area (ft}^2\text{)}}$$

Does your building envelope conserve energy sufficiently, or do you need more insulation (or less non-south glass or less infiltration)?

STEP 5. Determine the *vertical projection* of the solar opening area A_P. (For a vertical solar opening, A_P is identical to the actual opening area; for a 45°-inclined solar opening, A_P = 0.707 actual area.)

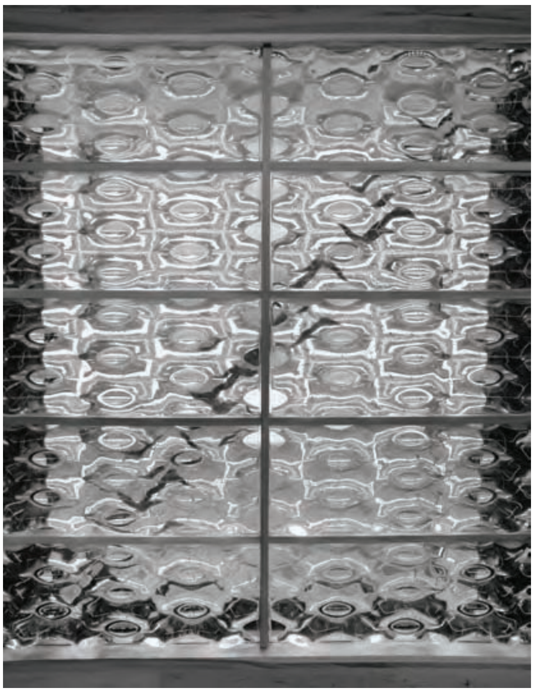


(*a*)

(*b*)

Fig. 9.12 *The San Luis Solar Group Complex near Santa Margarita, California, includes a house and an architectural studio. PV and micro-hydroelectricity generation joins daylighting, passive solar heating, and passive cooling in this innovative installation. (a) North–south section. (b) Exterior of a specially built water wall below a window serving the dining room. (Drawings courtesy of San Luis Solar Group, Santa Margarita, CA.)*

(*a*)



(*b*)

Fig. 9.13 *A water wall system (a) developed by the 2009 University of Arizona Solar Decathlon team built into the south wall of the dining room; (b) clear plastic water wall system allows filtered daylight through and acts as a heat sink during the day. (© Alison Kwok; all rights reserved.)*

STEP 6. Find the LCR, expressed in Btu/DD ft^2:

$$\mathrm{LCR} = \frac{\mathrm{BLC}}{A_P}$$

STEP 7. For the reference system that most closely approaches your design, consult Table I.3 for the appropriate location. By interpolation, find the annual SSF that corresponds to your passive system's listed LCR. Note also the annual DD65 listed in this table.

STEP 8. Finally, determine the approximate annual auxiliary heating Q required:

$$Q = (1 - \mathrm{SSF}) \times \mathrm{BLC} \times \mathrm{DD}$$

Although this quick annual-results method is based on the DD65 listed in Table I.3, it is possible to adjust Q to *approximately* account for higher internal gains or better-insulated envelopes. In this adjustment, use DD based on the balance point instead of DD65 in the previous equation.

STEP 9. Now compare the design-guideline-predicted relationship between collector size and SSF to the actual one you have just calculated. If the SSF is *smaller* than you had hoped, can you decrease BLC (improve conservation) or increase collector size, or switch to another passive system with a more favorable SSF for the same LCR? If the SSF is *larger*, will you be happy with the increased fuel savings, or will you reduce the collector size or consider another, less-efficient passive system that has some architectural advantage over the one for which you calculated SSF? Table G.4 shows approximate LCRs for four historic solar buildings.

EXAMPLE 9.4 We now take a more detailed look at the solar collecting area required for the passively solar-heated building in Omaha, Nebraska, discussed in Example 9.1.

SOLUTION

From the design guidelines used in Example 9.1, we expected that 20% of the floor area in south glass with superior performance would yield a 51% SSF. More detailed characteristics of this building are shown in Fig. 9.14. From a program requirement of 2900 ft^2 of floor area, the 20% south glass area equals $0.20 \times 2900 = 580$ ft^2. For daylighting by sidelight only, $\mathrm{DF_{av}} = 0.2$ (window area/floor area) refer to sidelighting guidelines in Chapter 8 Daylighting; if all of the south glass area is available for daylighting (as with DG systems), $\mathrm{DF_{av}} = 0.2 \times 20\%$, or 4%. This is adequate for office work. However, because you want to avoid dark areas near the rear walls of these spaces some north light is desirable. Choose about 3% of the floor area in north glass (say, 90 ft^2 glass); added $\mathrm{DF_{av}} = 0.2 \times 3\% = 0.6\%$ additional.

(Wall and roof insulation and overall percentage wall area in fenestration should be checked against the requirements of local codes and the current version of ASHRAE Standard 90.1.)

The fenestration area:

south glass 580 ft^2 + north glass 90 ft^2 = 670 ft^2

Total wall area:

north 1100 ft^2 + south 1100 ft^2 + east 600 ft^2 + west 600 ft^2 = 3400 ft^2

Fenestration/wall area ratio = 670 ft^2/3400 ft^2 = 20%

Coincidentally, this is also the percentage floor area in south glazing.

We will assume that the following maximum U-factors meet codes and standards and that ventilation at the rate of 20 cfm per person is provided. The building will house 2900 ft^2/180 ft^2 per person = 16 people. Ventilation airflow (in place of infiltration) = 20 cfm per person × 16 people = 320 cfm.

STEP 1. Given the emphasis on daylight and the original assumption of night ventilation with the windows, choose system DGC2. This has triple-glazed windows and will require six times as much thermally massive surface area (minimum 4-in. thick) as south glass area:

6×580 ft^2 south glass = 3480 ft^2 exposed thermal mass, minimum

If all interior surfaces of exterior walls are exposed concrete block, we obtain

3400 ft^2 wall total − 670 ft^2 window = 2730 ft^2 interior mass area

which is not sufficient. So, add at least 750 ft^2 exposed concrete slab floor area, such as a 10-ft-wide strip just inside the south windows, for the entire length of the building.

STEP 2. The solar opening was selected at 20% floor area, or 580 ft^2.

STEP 3. Calculate $\mathrm{UA_{ns}}$.

North, east, and west opaque (mass) walls: 2210 ft^2 × 0.08 = 177

South opaque (mass) wall: 520 ft^2 × 0.08 = 42

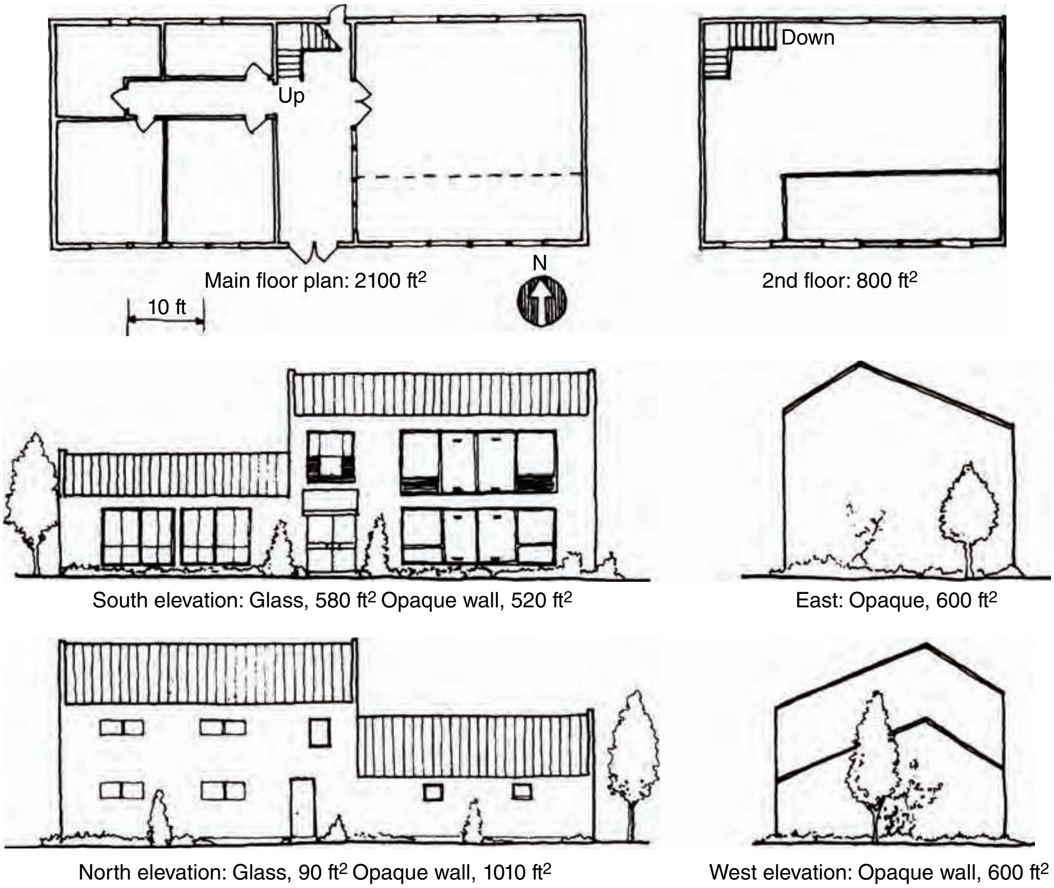


Fig. 9.14 *Plans and elevations of the Omaha, Nebraska, office building discussed in Example 9.4.*

Roof (insulation above deck): 1974 $ft^2 \times 0.048 = 95$

Slab perimeter: 200 lin ft $\times$ 0.54* Btu/h °F lin ft $= 108$

North glass: (triple-glazed, U = 0.33): 90 $ft^2 \times 0.33 = 30$

Ventilation: 320 cfm $\times$ 1.1 Btu min/h ft^3 °F = 346

Total 798 Btu/h °F

Then

$$\begin{aligned} \text{BLC} &= 798 \text{ Btu/h °F} \times 24 \text{ h/DD} \\ &= 19{,}152 \text{ Btu/DD} \end{aligned}$$

STEP 4. Calculate overall heat loss rate:

$$\frac{19{,}152 \text{ Btu/DD}}{2900 \text{ ft}^2} = 6.6 \text{ Btu / DD ft}^2$$

*From Table E.11, assuming insulated construction type (a), with R = 5.4 insulation, and interpolating for 6601 DD65.

This is considerably in excess of the Table 9.1 criterion of 4.6 Btu/DD ft^2 for this 6300 DD65 climate. Unless further conservation steps are taken, the annual SSF is likely to be much lower than was predicted by the design guideline. Promising targets: more insulation on the wall, slab edge, and roof; a heat exchanger for that 320 cfm of outdoor air.

STEP 5. Determine the vertical projection of the solar opening. The south windows are vertical; therefore, A_P is identical to the actual area, 580 ft^2.

STEP 6. Find the LCR:

$$\frac{19{,}152 \text{ Btu/DD}}{580 \text{ ft}^2 \text{ floor}} = 33.0$$

STEP 7. From Table I.3 for Omaha, Nebraska, look up LCR = 33, and DGC2. Interpolate between LCR 30 and 40. The annual SSF is found to be about 29.2%.

STEP 8. The approximate annual auxiliary heating required is

$$Q = (1 - 0.292) \times 19{,}152 \times 6300 \text{ DD}$$
$$= \text{about } 85{,}425{,}500 \text{ Btu}$$

STEP 9. Compare the actual SSF with the predicted value: SSF = 29.2% is only about three-fifths of the 51% SSF predicted by the guideline, as a result of inadequate conservation measures, as explained in Step 4. A lower LCR yields a higher SSF; and a larger collector area would lower the LCR. However, Step 4 indicated that lower BLC, not higher A_p, is the better way to achieve a lower LCR in this case.

Table I.3 can be used to compare the relative performance of many passive heating systems. Using the column of LCR = 30, for instance, the best-performing systems are:

Omaha, Nebraska, LCR = 30	
WWB4	47% SSF
WWC2	45%
SSE2	44%
DGC3	42% (movable insulation)
TWD4	42%
TWE2	42%

If any one of these systems is more architecturally compatible with the building program and/or design intent, it could be used instead of DGC2. In this case, DGC2 gives substantial daylighting with little impact on the exterior appearance; the large area of thermal mass necessary was relatively easily obtained. DGC2 appears to be a reasonable choice for this building in this climate, if the client prefers not to use movable insulation over windows. ■

What if two or more passive systems are used in the same building? In that case, first do calculations for the entire building, assuming that *one* system has *all* the solar area, and find the SSF. Next, do the calculations assuming that the second system has all the solar area, and find its SSF. Then average the SSF values according to the relative solar areas of the two systems.

EXAMPLE 9.5 A veterinary clinic in Buffalo, New York, is using two systems: WW for examination rooms and DG for the waiting/reception area. The building's characteristics are

Balance point = 50°F

UA_{ns} = 356 Btu/h °F

A_p WW = 240 ft^2 (reference system WWB4)

A_p DG = 150 ft^2 (reference system DGA3)

Total floor area = 1900 ft^2

Predicted SSF for a generic system from design guideline = about 36%, superior performance

Checking the overall heat loss criteria (Table 9.1),

$$\frac{356 \times 24}{1900 \text{ ft}^2} = 4.5 \text{ Btu/DD ft}^2$$

This is less than 4.6 (for 5000 to 7000 DD), so it is acceptable.

SOLUTION

First, calculate as though all A_p (390 ft^2) were system WWB4:

$$\text{BLC} = 24 \times 356 = 8544 \text{ Btu/DD}$$

$$\text{LCR} = \frac{8544}{390} = 22$$

For Buffalo, LCR 20 yields SSF = 0.37, and LCR 25 yields SSF = 0.31, so SSF = 0.35 by interpolation.

Next, calculate as though all A_p were system DGA3. For LCR 22, Buffalo SSF = 0.28 by interpolation.

Now calculate the average SSF, given that the WW comprises 240/390 = 62% of the total solar opening and DG comprises 150/390 = 38%:

$$\frac{0.35(62\%) + 0.28(38\%)}{100\%} = 0.217 + 0.106$$
$$= 0.323;\ \text{SSF} = 0.32$$

Result: The SSF is about 90% of what was first predicted (0.32 as opposed to 0.36); because the glass area is already large, program requirements probably prevent further increases. The building already seems to conserve energy well, because it meets the Table 9.1 heat loss criteria.

The approximate annual auxiliary heating energy required is

$$Q = (1 - 0.32) \times 8544 \text{ Btu/DD}$$
$$\times 3322 \text{ DD50 (balance point)}$$
$$= 19 \text{ million Btu}$$

(This is equivalent to about 5600 kWh, or about 220 therms of natural gas burned at 85% efficiency.) ■

(g) Variations on Reference Systems

A particularly wide set of choices faces the designer of DG and SS systems, in which mass distribution and glass orientation can assume thousands of different combinations. The *sensitivity curves* furnished in Balcomb et al. (1984) give some guidance on how a predicted SSF might vary as an actual passive system departs from a reference system.

Sensitivity curves can serve as early general design guidelines. Looking at the curves for your location, which design changes yield dramatic results, and which make little difference? The curves may also be used to adjust the SSF found for a reference design.

One passive solar example that departs radically from any reference case is the Class of 1959 Chapel at the Harvard Business School in Cambridge, Massachusetts (Fig. 9.15). The glazed "sunspace" resembles system type SSA in that it is attached to (rather than set into) the building behind it. However, this is manifestly *not* the simple rectangular SS plan, and the solar aperture is divided into southeast- and southwest-facing halves. The aperture A_p is doubly complicated: The vertical dimension is the vertical projection of the sloping wall, whereas the horizontal dimension is the due-south projection of the plan. From Table I.1, because of the glazed end walls and masonry common wall, it comes closest to either SSA3 (standard performance) or SSA4 (superior performance). This depends upon the glazing chosen—in this case, clear double glazing with low-ε, air space approximately ½-in. (13-mm) thick. In Cambridge (Boston), for a small LCR (a huge solar aperture relative to the building behind), the Balcomb reference shows:

If LCR	=	25	20	15
If SSA3, then SSF	=	37	41	47
If SSA4, then SSF	=	55	61	69

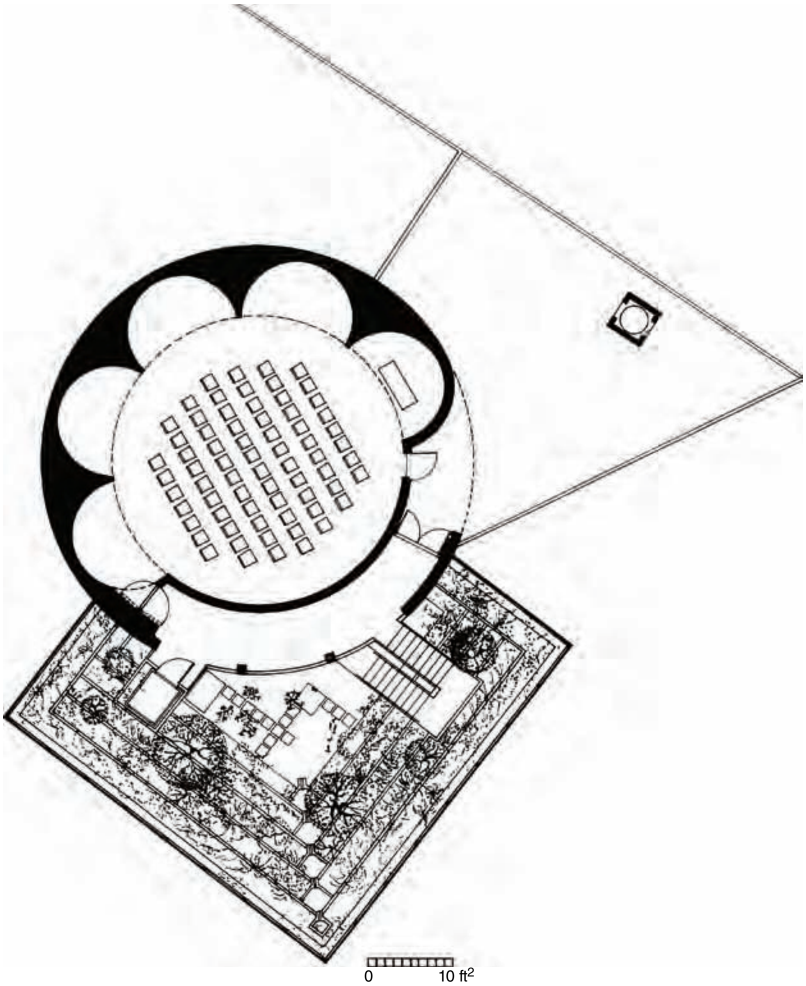
Given the complex geometry of this SS, the safer assumption is standard performance.

Water walls are rather uncommon in buildings, despite their relatively high performance throughout Table I.3. These systems are based on opaque containers, but some designers are attracted by the idea of daylight filtering through translucent water containers. Algae growth in transparent plastic tubes, encouraged by the daylight that passes through them, is usually controlled by the addition of an algaecide to the water. Dyes may be added to change the color of daylight seen through tubes or water-filled glass block, as in Fig. 9.16. The "WW" of this Long Island library is actually a hybrid between DG (light passes through the glass to strike massive surfaces beyond) and WW (all radiation is converted to heat within the opaque

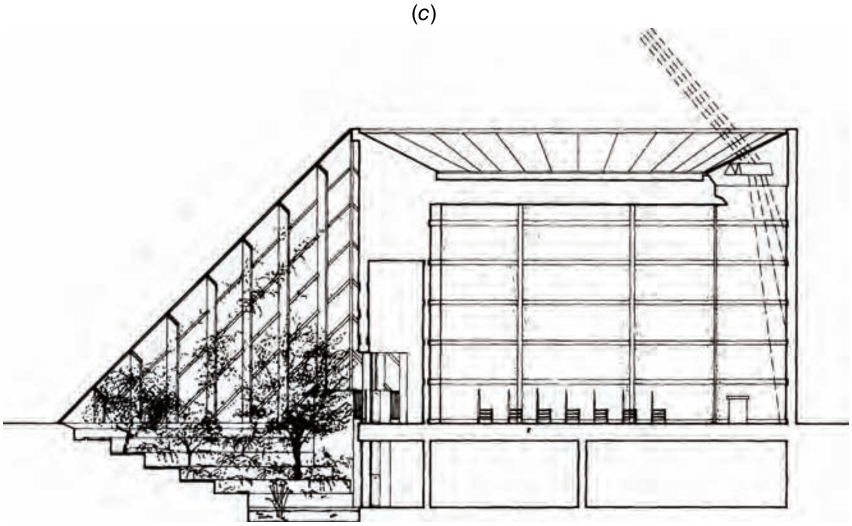
(*a*)

(*b*)

Fig. 9.15 *The Class of 1959 Chapel at the Harvard Business School features (a) south-facing glazing of the sunspace and (b) a sunken garden in the sunspace. (c) Plan; south is about 30° east of the point of the sunspace. (d) Section. This is not a typical sunspace type from Appendix I. (© Thomas Collins; used with permission; Drawings courtesy of Moshe Safdi and Associates, Inc., Somerville, MA.)*



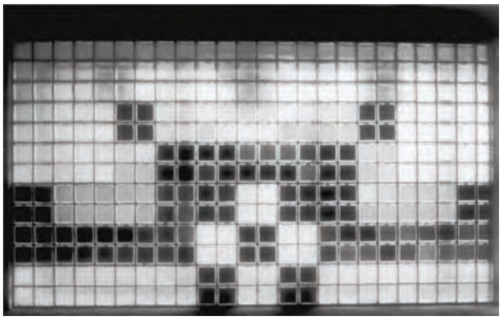
(*c*)



(*d*)

Fig. 9.15 *(Continued)*

(*a*)



(*b*)

Fig. 9.16 *The Center Moriches Free Public Library (Long Island, New York) utilized water-filled glass block as a heat storage and daylight-diffusing south wall (a). Because the water storage is translucent, it functions somewhere between a DG and a WW system. Dyes add color to selected blocks, forming the pattern shown (b). Lightshelves and stack ventilators add to its energy-conserving performance. (Courtesy of Banwell White Arnold Hemberger & Partners, Architects, Hanover, NH.)*

TABLE 9.7 Time Lag through Homogeneous[a] Walls

Material	Thickness (in.)	U-Factor[b] (Btu/h ft^2)	Time Lag (h)
Stone	8	0.67	5.5
	12	0.55	8.0
	16	0.47	10.5
	24	0.36	15.5
Solid concrete	2	0.98	1.1
	4	0.84	2.5
	6	0.74	3.8
	8	0.66	5.1
	12	0.54	7.8
	16	0.46	10.2
Common brick	4	0.60	2.3
	8	0.41	5.5
	12	0.31	8.5
	16	0.25	12.0
Face brick	4	0.77	2.4
Wood	1/2	0.68	0.17
	1	0.48	0.45
	2	0.30	1.3
Insulating board	1/2	0.42	0.08
	1	0.26	0.23
	2	0.14	0.77
	4	0.08	2.7
	6	0.05	5.0

Source: Victor Olgyay, *Design with Climate: Bioclimatic Approach to Architectural Regionalism*, Copyright © 1963 by Princeton University Press. Reprinted by permission.

[a]For composite constructions, add an estimated additional time lag to the sum of the individual materials' time lags as follows:

Two-layer, light construction:	½ hour more
Three or more layers:	1 hour more
Very heavy construction:	1 hour more

[b]The U-factor is based on outdoor surface conductance of 4.0 and an indoor surface conductance of 1.65 Btu/h ft^2 °F.

water containers, then passed to the space beyond). To assess the performance of such a system, interpolate between the entire aperture considered as the relevant DG system and the same entire aperture considered as the relevant WW system. The higher the visible transmittance, the closer to DG performance will be the result.

(h) Thermal Lag through Mass Walls

The time necessary for solar heat to pass through various thermally massive materials is shown in Table 9.7. This time lag can be put to use when the time of maximum solar heat is different from the time of maximum internal heat need. A typical example is for a residence's living room in winter, in which the late evening sedentary entertainment hours occur with cold temperatures outside, yet maximum warmth is desired inside. A Trombe wall, for instance, made of solid grouted concrete block and 12 in. thick, will delay the arrival of maximum solar gain to the interior by almost 8 hours. If maximum solar heat gain occurs at about 1:00 P.M. (maximum sun at noon but highest temperatures at about 2:00 P.M.), then such a TW would deliver the maximum heat to the inner surface at about 9:00 P.M.

(i) Internal Temperatures

Two quantities are of particular interest to passive solar designers. How much higher, compared to the outdoor temperature, will the average indoor temperature be from solar heating alone? Also, how widely will this internal temperature vary (swing) on a clear winter day?

The approximate temperature difference between inside and outside on a *clear* January day, called Δt *solar*, can be estimated from Fig. 9.17; it varies with latitude and with the LCR. Sunspaces are not shown in the figure. Although the temperature within an SS cannot be easily approximated, the Δt solar for the room beyond the SS can be approximated by using Fig. 9.17*a*, if these spaces have an insulated common wall, or Fig. 9.17*b* if they have a masonry common wall.

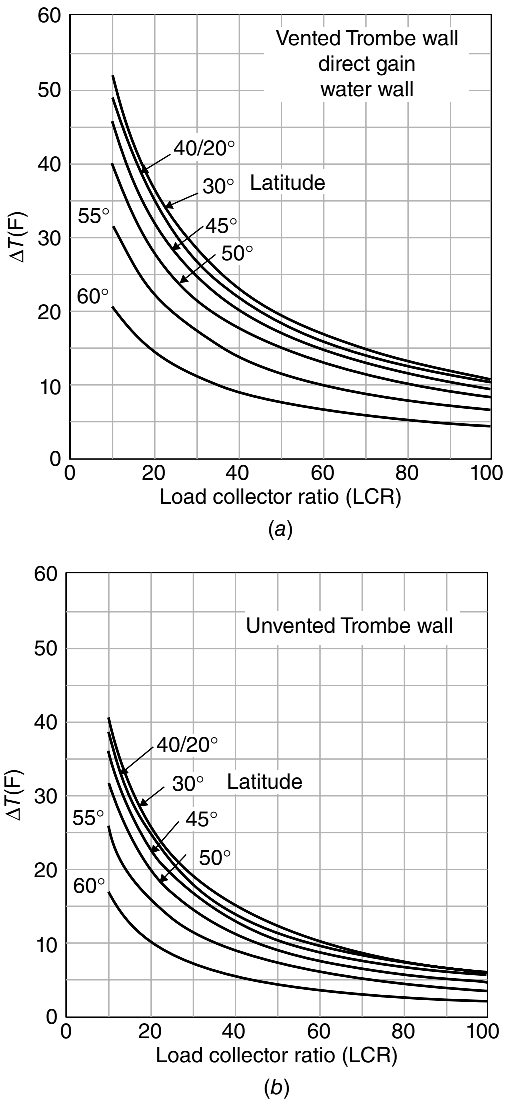


Fig. 9.17 *Graphs of* Δt *solar, the temperature difference to be expected between the average inside temperature and the average outside temperature on a clear January day. The curve marked 40/20° applies to both 40° latitude and 20° latitude. (a)* Δt *solar for direct gain, water wall, vented Trombe wall, or sunspace (insulated common wall) systems. (b)* Δt *solar for unvented Trombe wall or sunspace (masonry common wall) systems. (From Balcomb et al., 1980.)*

To determine the average winter indoor temperature:

1. Find the average January ambient (outdoor) temperature, *TA*, from Appendix C.
2. Find Δt solar for the building and its site latitude (Fig. 9.17).
3. Find the Δt due to internal heat sources:

$$\Delta t \text{ internal} = \frac{\text{total internal gains (Btu/day)}}{\text{BLC} + (UA_s \times 24)}$$

   where UA_s is for the solar area only. Note: Δt internal averages 5 to 7F° for residences.
4. Add the quantities from the first three steps to find the average January clear-day indoor temperature.

When internal gains are high, there is less need for Δt solar; the building is mostly "heating itself" (becoming an internally load dominated rather than an skin load dominated building). If the average indoor temperature is too high, smaller solar openings should be considered, unless the climate is predominantly cloudy (clear days rare) in November through January.

The other important comfort question concerns the size of the *temperature swing* due to passive solar heating. Controlled by the sun and by the actions of users rather than by a thermostat, passive solar buildings typically experience larger daily variations (swings) in indoor temperature than do conventional buildings, especially on clear days. To estimate your building's clear-day January temperature swing, or Δt *swing*, see Table 9.8. The average indoor temperature determined previously will fall in the middle of this Δt swing.

TABLE 9.8 Indoor Temperature Swing, Δt Swing

Passive Solar System	Δt Swing[a]
DG: $\frac{\text{mass area}}{\text{glass area}} = 1.5$	$1.11 \times \Delta t$ solar
$= 3$	$0.74 \times \Delta t$ solar
$= 9$	$0.37 \times \Delta t$ solar
WW	$0.39 \times \Delta t$ solar
TW, vented for 3% of wall area	$0.65 \times \Delta t$ solar
TW, unvented	$0.13 \times \Delta t$ solar

Source: Balcomb et al. (1980).

[a]These swings are based on a thermal storage mass capacity of 45 Btu/ft^2 °F; Δt solar can be found in Fig. 9.17.

9.7 CASE STUDY—DESIGNING FOR PASSIVE HEATING

Blue Ridge Parkway Destination Center, Asheville, North Carolina

Project Basics

- Location: Asheville NC, USA
- Latitude: 35.57° N; longitude: 82.57° W; elevation: 2300 ft (652 m) Asheville Airport
- Heating degree days: 4308 base 65°F (2393 base 18.3°C); cooling degree days 3365 base 50°F (1869 base 10°C); annual precipitation: 31 in. (787 mm)
- Building type: New construction; information and orientation services, exhibition spaces, theater, retail shop
- Building area: 12,000 ft^2 (1115 m^2) floor area
- Completed: December 2007
- Client: National Park Service (Southeast Region)
- Design team: Lord, Aeck & Sargent, Inc. (and consultants)

Background. The Blue Ridge Parkway Destination Center, located near Asheville, North Carolina, is a visitor center for the National Park Service located adjacent to the Blue Ridge Parkway headquarters. The Destination Center was developed as a partnership between the National Park Service and the Blue Ridge National Heritage Area to provide information about the Parkway's history and the nearby region between the Shenandoah and Great Smoky Mountains National Parks. Completed in 2007, the Destination Center is a demonstration of high-performance and ecological design. Park Superintendent Philip Francis noted that the Destination Center "embraces themes central to the protection, preservation, and thoughtful promotion of the cultural and natural heritages of western North Carolina as well as the entire Blue Ridge Parkway." The Destination Center features a variety of program areas including innovative, interactive exhibits, multimedia information about nearby places to visit, and a 70-seat surround-sound theater that shows a high-definition film about the Parkway, its history, and the region's cultural and natural sights and sounds. The design of this green building was a direct response to regional climate conditions, featuring uniquely

Fig. 9.18 *Blue Ridge Parkway Destination Center near Asheville, North Carolina. (© Evan Danchenko; used with permission.)*

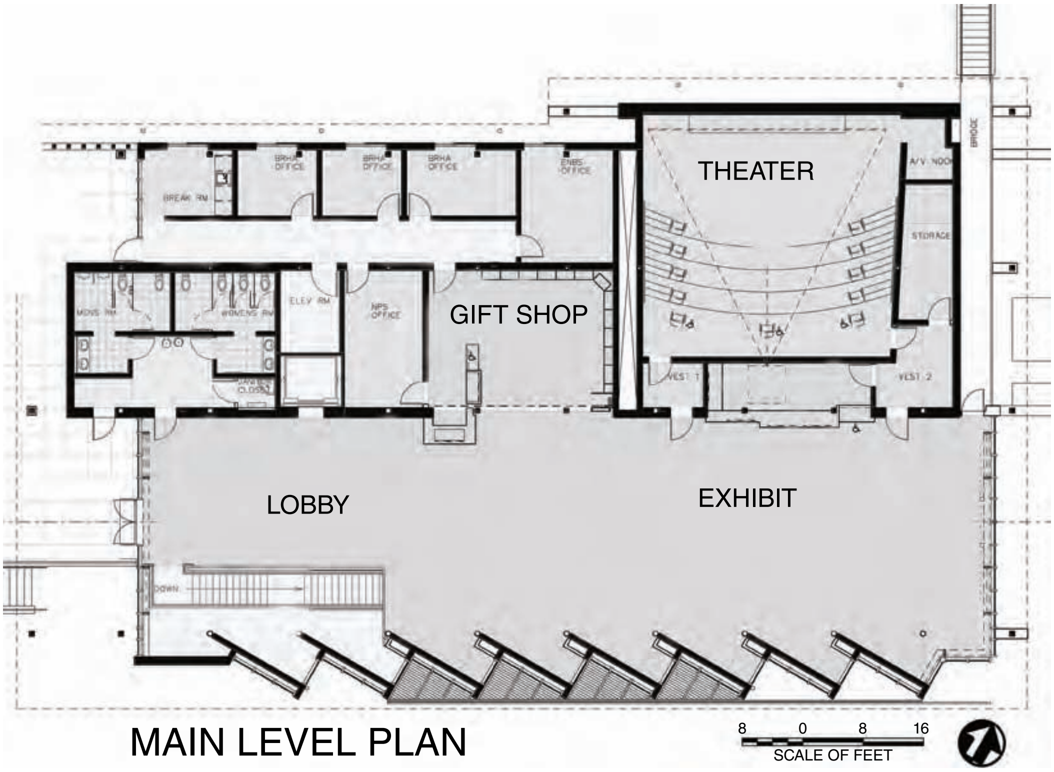


Fig. 9.19 *Main floor plan showing orientation and internal organization (© Lord, Aeck & Sargent, Inc.; used with permission.)*

(*a*) (*b*)

Fig. 9.20 *(a) South-facing, sawtooth Trombe wall with shading to prevent overheating in the summer; (b) North-facing glazing into the gallery and air intakes. (© Evan Danchenko; used with permission.)*

Fig. 9.21 *Exhibit space along the Trombe wall; note supply vents in the edges of the Trombe wall. (© Evan Danchenko; used with permission.)*

Fig. 9.22 *Interior exhibit space along the Trombe wall. (© Evan Danchenko; used with permission.)*

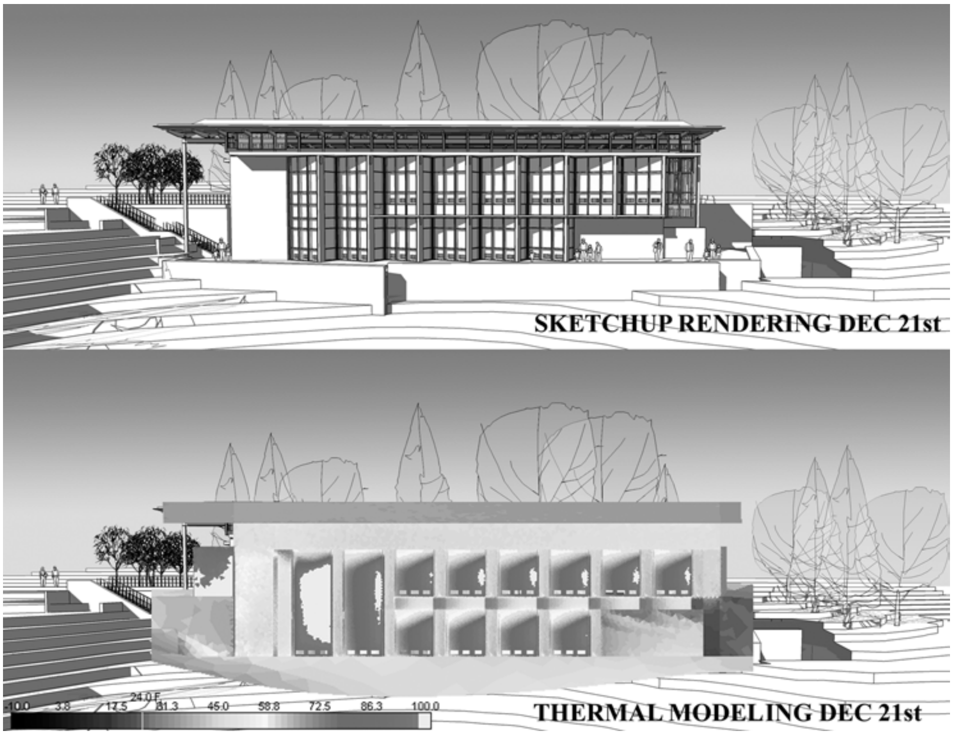


Fig. 9.23 *Images from the shading and thermal performance analyses of the Trombe wall. (© Lord, Aeck & Sargent, Inc.; used with permission.)*

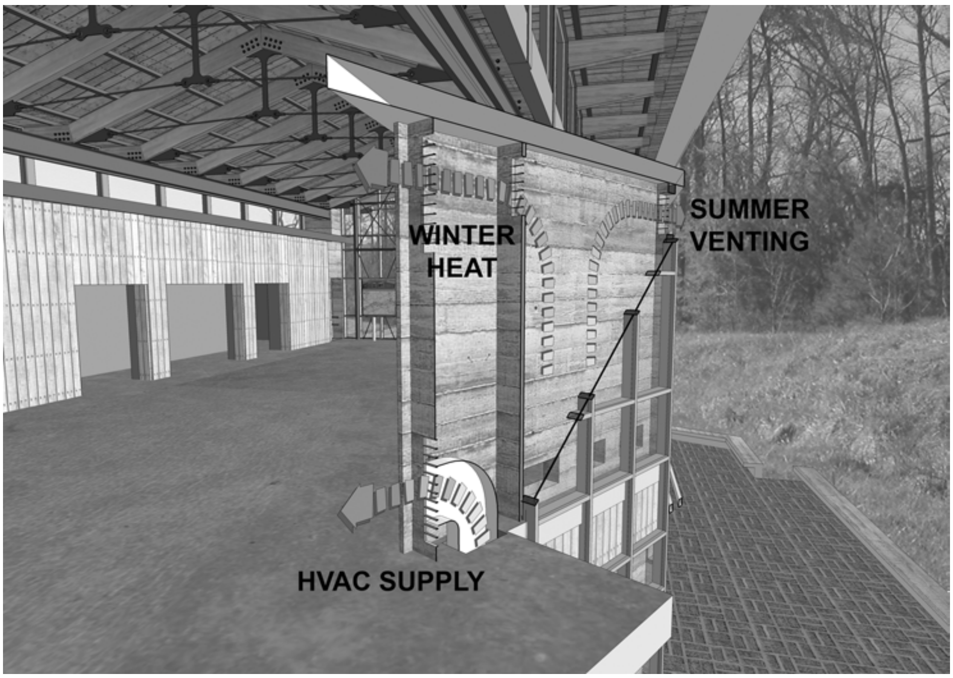


Fig. 9.24 *Diagram showing integrated uses of the Trombe wall as a structural element along the exhibit space with summer venting, winter heating supply, and supplemental HVAC supply. (© Lord, Aeck & Sargent, Inc.; used with permission.)*

integrated Trombe walls, a green roof, radiant floors, energy recovery, occupancy sensors, and daylighting. The design team projected that the building will use 75% less energy than a minimally code-compliant building.

Context. Ideal passive solar orientation suggests a building along an east–west axis; however, existing site topography required that the building be oriented 30° west of south to minimize regrading and protect existing vegetation. In the moderate, yet heating-dominated climate of Asheville, the use of passive solar heating offered a clear opportunity to conserve energy. The relatively benign cooling season and low evening temperatures allow for natural ventilation and nighttime ventilation of thermal mass. To optimize the exposure along the southern façade, the designers created a sawtooth-shaped façade, integrating multiple functions of structure, exhibit space, Trombe walls, and ventilation cavities. Climate analysis and preliminary energy modeling guided the schematic design process.

Design Intent. The Destination Center takes advantage of its geographic location by utilizing the climate for passive solar strategies as well as providing spectacular views of the natural beauty of the Parkway.

In addition to the National Park Service's philosophy of pedagogic environmental interpretive centers, the ecological and energy-efficient building design was guided by the design team's green design philosophy. Some of the key project goals were:

- Achieve Leadership in Energy and Environmental Design (LEED) Gold certification.
- Reduce energy loads through passive strategies (daylighting, passive heating, increased envelope insulation, natural ventilation, green roof).
- Provide additional conditioning through appropriate, efficient HVAC system design (radiant heating, energy recovery).
- Provide a Destination Center that reflects the deep green design philosophy of the design team.
- Complement the natural beauty of the Parkway and provide a "tree-house" atmosphere.
- Reduce solar gain in the summer through appropriate orientation and shading.
- Increased adaptive comfort opportunities through passive design strategies.

Design Criteria and Validation. A USGBC LEED Gold certification was awarded to this project. The design team used DOE-2.2 (eQUEST v 3.6) in preliminary analysis to estimate overall energy use. Space heating accounted for 65% of the overall building energy use, and lighting, fans, and space cooling constituted 28% of the remaining loads. Additional energy models run without an HVAC system estimated that the Trombe wall would provide temperatures approximately 8F° (4.4C°) above that of a standard high-mass building with optimized orientation, and approximately 30F° (17C°) above exterior dry-bulb temperatures. Computational fluid dynamics (CFD) analysis conducted by Pennsylvania State University's Applied Research Laboratory assessed the building in passive mode and showed the benefits of the Trombe walls in the winter—projecting a system effect of a 30F° to 40F° (17C° to 22C°) increase above the outside temperature.

Post-Occupancy Validation Methods. A week-long post-occupancy monitoring was performed during the first winter of occupancy to compare the performance of the Trombe walls with the simulations. The architects, along with students from Georgia Tech University, conducted the monitoring.

Performance Data. Information available to date suggests substantial design team success in ecological design:

- The project earned LEED Gold certification in 2009.
- On sunny days the Trombe walls were running 35F° to 40F° (19C° to 22C°) higher than outdoor temperatures, and 30F° to 35F° (17C° to 19C°) higher at night, correlating well with the preliminary CFD findings.

FOR FURTHER INFORMATION

Lord, Aeck & Sargeant: http://www.lordaecksargent.com/

Moffit, Debra, "Appalachian Suncatcher," *ArchitectureWeek*, No. 381. May 21, 2008.

Parkway Destination Center: http://www.architectureweek.com/2008/0521/index.html

References and Resources

ASHRAE. 2013. ANSI/ASHRAE/IESNA Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2009. *ASHRAE Handbook—Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2012. *ASHRAE Handbook—Systems and Equipment*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Balcomb, J. D., D. Barley, R. McFarland, J. Perry, Jr., and W. Wray. 1980. *Passive Solar Design Handbook, Vol. 2, Passive Solar Design Analysis*. U.S. Department of Energy. Washington, DC.

Balcomb, J. D., R. Jones (ed.), R. McFarland, and W. Wray. 1984. *Passive Solar Heating Analysis.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Brown, G. Z., B. Haglund, J. Loveland, J. Reynolds, and S. Ubbelohde. 1992. *InsideOut: Design Procedures for Passive Environmental Technologies*, 2nd ed. John Wiley & Sons. New York.

Johnson, T. 1981. *Solar Architecture: The Direct Gain Approach*. McGraw-Hill. New York.

Mazria, E. 1979. *The Passive Solar Energy Book*. Rodale Press. Emmaus, PA.

Olgyay, V. 1963. *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton University Press. Princeton, NJ.

SERI. 1981. *A New Prosperity: Building a Sustainable Energy Future, The SERI Solar Conservation Study*. Brick House Publishing. Andover, MA.

Stromberg, R.P. and S.O. Woodall. 1977. *Passive Solar Buildings: A Compilation of Data and Results*, SAND-77-1204. Sandia Labs. Albuquerque, New Mexico.

Wittwer, V., W. Platzer, and M. Rommell. 1991. "Transparent Insulation." *Solar Today*, January–February, 1991.

CHAPTER 10

Passive Cooling

DEPENDING ON THE LOCATION AND SEASON, human beings have always searched for suitable ways to improve or stabilize conditions for comfort. Some say that we have been most successful in controlling environments that require heat and maintaining warmth during cold seasons. However, across much of the planet, passive cooling strategies have been practiced for thousands of years and remain part of the vernacular culture of building in many countries.

Controlling heat that a building gains from its environment is the first step in passive cooling design (as it is with passive heating). Passive cooling strategies can literally introduce "coolness" into a building without mechanical assistance—essentially exhausting the building of unwanted heat gains without any mechanical fans or energy.

The information in this chapter is organized from general to specific. General guidelines are given as a starting point for preliminary passive cooling sizing for typical buildings; these include determining heat gains, appropriate opening sizes, and thermal mass. Designers can make quick approximations to determine if the design is on the right track. As the building takes shape, more detailed information becomes useful and a section with more detailed calculation procedures will allow the designer to select a passive cooling approach with some confidence in its applicability and the need for auxiliary space cooling. A number of example exercises and solutions for the various strategies will demonstrate how to start making these schematic design calculations.

10.1 BRIEF HISTORY

Just as the Greeks and the Chinese practiced solar design planning for proper solar orientation and passive heating, there was also an understanding of shading and evaporative cooling (fountains, pools, water streams, and vegetation) in hot, dry conditions to accomplish cooling effects in and about buildings. Earth-sheltered dwellings used the massive construction to dampen temperature swings, block direct solar radiation, and provide "coolth" in desert climates. In hot, humid climates, where cross-ventilation is desirable, it becomes advantageous to have large shaded verandahs, shading devices, large openings to admit breezes, and structures raised above the ground to allow breezes to flow beneath.

With more affordable air-conditioning systems, hotter cities (urban heat islands), and people's changing expectations about comfort, often the passive approach is abandoned in favor of a total dependence on mechanical equipment. The green building movement and improved building techniques have reconsidered passive cooling principles as part of new integrated, high-performance designs. The cooltower at the Global Ecology Research Center at Stanford University (Fig. 10.1) uses simple technology, with a mister (equivalent to a wetted pad) at the top where hot, dry air enters. As water evaporates inside the tower, the air temperature drops (the moisture content of the air increases), and the denser air drops to the

Fig. 10.1 *Evaporative cooltower at the Global Ecology Research Center at Stanford University, Menlo Park, California (© Alison Kwok; all rights reserved.)*

opening in the base, exiting in this case to the lobby of the building.

10.2 DESIGN STRATEGIES FOR COOLING

Taking into consideration site conditions such as location, orientation, wind, land massing, vegetation, and microclimate, a designer will develop screens, shading, wingwalls, building exposure, openings, and other features to follow four basic approaches to control the heat gains in a building: natural ventilation cooling (cross and stack ventilation), high-mass cooling (roof ponds, earth contact), night ventilation of thermal mass, and evaporative cooling. All take advantage of the concept of "heat sinks" whereby heat will move to a cooler area.

The various approaches to passive cooling in temperate climates are best assessed on the *building bioclimatic chart* (Fig. 10.2) developed by Milne and Givoni (1979). The chart allows the designer to visualize the suitability of four approaches to passive cooling under summer conditions.

Average monthly climate data (as in Table 10.1) are now available from software and various websites (see Appendix L). Such climate data can be plotted on this chart. If they do not exceed the "boundaries" of a strategy zone, then a match is indicated between the climate and that strategy. Although the edges of each strategy zone are drawn as lines, these boundaries are more broad and vague than the lines suggest. When a climate surpasses the boundaries of all four strategy zones, conventional air conditioning is almost certainly desirable.

To plot average monthly conditions for a climate on this strategy chart, assemble information such as that shown in Table 10.1. This is available for every climatological station maintained by the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of

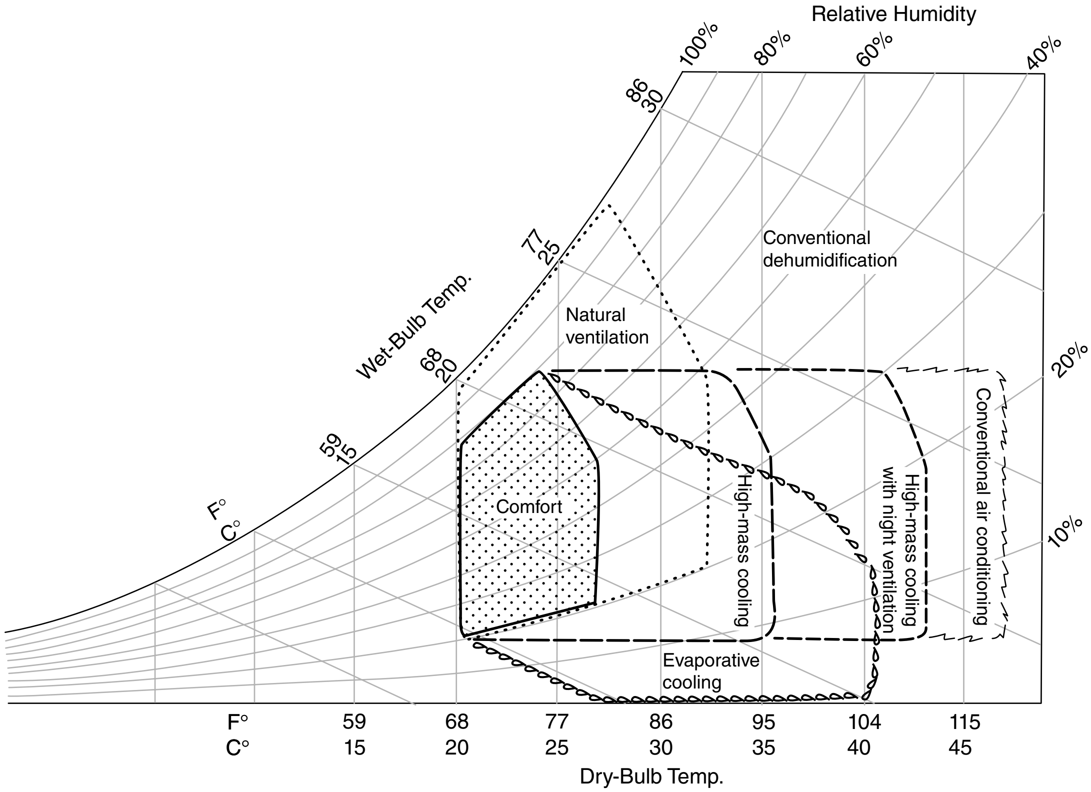


Fig. 10.2 *Passive cooling design strategies by climate. After plotting the outdoor climate data on this chart, consider how that information would affect a design strategy. (Based upon Milne and Givoni, 1979.)*

Commerce. These climate summaries, often called LCDs (Local Climate Data), are available from the National Climatic Data Center (Federal Building, Asheville, NC 28801). Many libraries also carry such summaries in publications such as *Climates of the States.*

In addition to a typical hot summer day, it is useful to check for the *design condition*, the statistically relevant condition for which engineers would design a building's mechanical cooling equipment. The design condition shows the climate near its worst, while avoiding the freakish conditions of extreme temperatures listed in the NOAA data. Summer (and winter) design data are available in Appendix B (along with discussion of the nature of the data).

TABLE 10.1 Normal Data from Annual Summary of Local Climatological Data for Dodge City, Kansas[a]

	Daily Temperatures °F (°C)				*Relative Humidity (%) at Hour*				*Wind*	
	Normal		*Extreme[b]*							
Month	**Max**	**Min**	**Max**	**Min**	**00**	**06**	**12**	**18**	**Mean Speed Mph (km/h)**	**Prevailing Direction**
June	86.0 (30.0)	61.4 (16.3)	108 (42.2)	41 (5.0)	63	75	44	38	14.4 (23.2)	South
July	91.4 (33.0)	66.9 (19.4)	109 (42.8)	47 (8.3)	66	78	46	42	12.9 (20.8)	South
August	90.4 (32.4)	65.7 (18.7)	107 (41.7)	47 (8.3)	71	80	50	46	12.7 (20.5)	South

[a]Records as of 1979.

[b]Extremes do not occur on the same day or series of days.

EXAMPLE 10.1 To determine the viable passive strategies for Dodge City, Kansas, plot the typical day of the hottest month on the bioclimatic chart.

SOLUTION

By inspection of Table 10.1, the hottest month is July, but August is close, and sun angles are lower (more gain through windows). To chart the typical August day, find the approximate RH for the coldest and hottest hours. Because RH is listed only at four times, first select the highest RH, occurring here at 6:00 A.M.; this will coincide approximately with the coldest hour. Thus, one end of the linear climate plot for August in Dodge City will be at the combination of 80% RH and 65.7°F (18.7°C). The other end of the plot will be at the lowest RH and the hottest hour, in this case at 6:00 P.M., a combination of 46% RH and 90.4°F (32.4°C). The line between these points is shown in Fig. 10.3.

From Fig. 10.3 one passive cooling strategy—high mass with night ventilation—appears clearly adequate to meet the needs of the typical August day in Dodge City. (Using this strategy, the low-temperature end of the line is also important and should be below the comfort zone for best results.) Another strategy, high mass, appears just barely adequate. Two other strategies, natural ventilation and evaporative cooling, appear inadequate because the highest temperature/lowest RH combination falls outside their boundaries—slightly so for natural ventilation, but greatly so for evaporation.

Using design climate data corresponding to the values in Table 10.1, the summer DB and mean coincident WB temperature is 97/69°F (36.1°C/20.6°C); this combination is shown as a circle around the point in Fig. 10.3. The 97°F (36.1°C) DB temperature is plotted on the corresponding vertical line; the 69°F (20.6°C) WB temperature is found by first locating the 69°F (20.6°C) DB vertical line and following that line up to 100% RH, where 69°F (20.6°C) DB and WB are coincident. Then follow downward to the right along the constant WB line to its intersection with 97°F (36.1°C) DB.

The design condition point falls just outside the zone of high-mass cooling and just within the zone

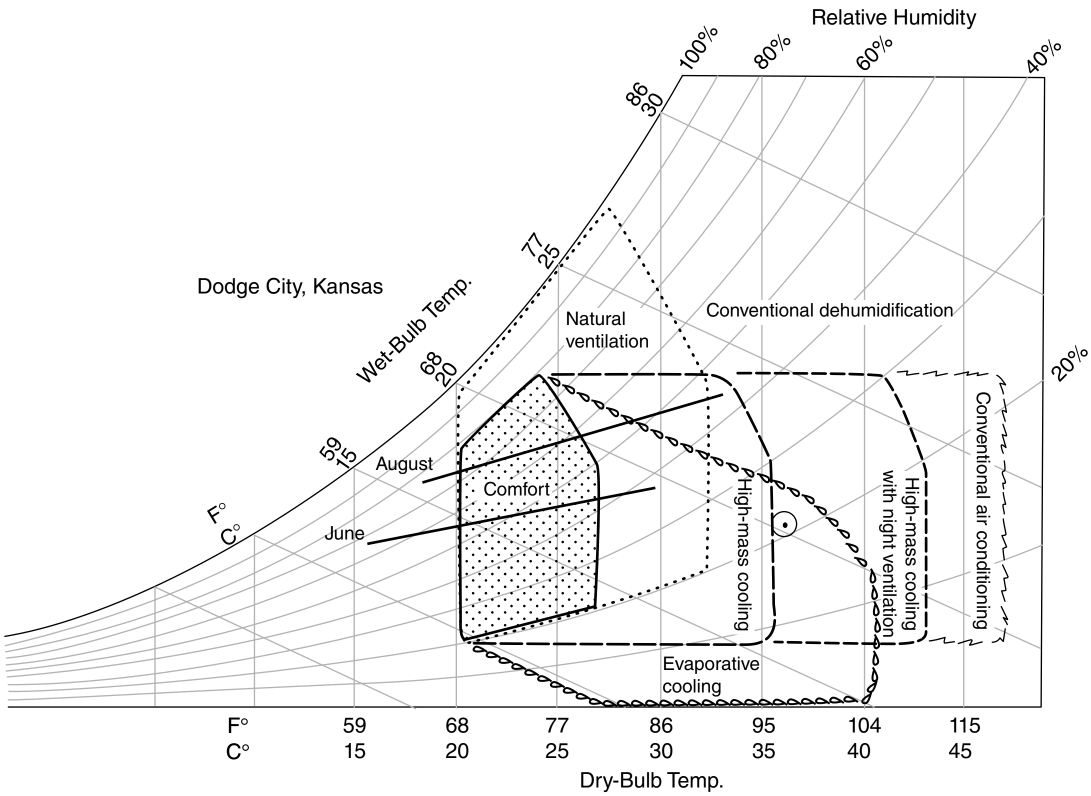


Fig. 10.3 Hot-month daily ranges and the summer design condition for Dodge City, Kansas, superimposed on the design strategy chart of Fig. 10.2.

of evaporative cooling. Because the design condition falls well within the zone of high mass with night ventilation, this strategy is thus confirmed as clearly the best of the passive cooling strategies for Dodge City. ■

(a) Natural Ventilation Cooling

This is the most obvious strategy suggested by the comfort charts presented earlier, in which higher air temperatures were offset by increased air motion. It may be the only passive strategy available in humid, hot climates in which temperatures are only slightly lower by night than by day. Buildings should be very open to breezes while simultaneously closed to direct sun. The materials of these buildings may be thermally lightweight as well, because the temperature of the night air is not cool enough to remove much stored daytime heat. Very high humidity may be avoided only by sealing and air-conditioning buildings.

Natural ventilation has two variations: cross-ventilation and stack ventilation. *Cross-ventilation* is driven by wind and is accomplished with windows. It relies upon rather narrow plans with large ventilation openings on either side. Thus, it is naturally compatible with daylighting. *Stack ventilation* depends upon very low openings to admit outdoor air and very high openings to exhaust air; it is driven by the principle that hot air rises. Stack ventilation is generally weaker than cross-ventilation—except when there is no wind at all.

(b) High-Mass Cooling

This strategy is most successful in locations with warm, dry summers, where the extremes of hot days can be tempered by the still-cool thermal mass of a building. Cool nights then slowly drain away the heat that such mass accumulates during the day. The thermal mass can be located in floors, walls, or roofs but will need a *sink* to which it can reject its heat by night. The roof has the advantage of radiating to the cold night sky, but it should be protected from exposure to sun by day. The masonry courtyard-type buildings of the Mediterranean are vernacular examples of this passive cooling strategy; their courtyard floors and roofs can be protected with movable shading devices (*toldos*) by day, then opened to night-sky radiation.

Roof ponds are a form of high-mass cooling for one- and two-story buildings. Because they require only the roof to be massive, they allow for considerable design freedom in walls and fenestration. Where cooling is the only objective, this approach uses water that is stored between the metal ceiling and the roof insulation; by night, the water is pumped (and/or sprayed) over the exposed roof surface and allowed to trickle back through the insulation to the storage pond. At lower latitudes (with high winter sun altitudes), roof ponds can be used for passive solar heating as well. This strategy uses sliding panels of insulation over bags of water; the panels slide open on winter days to collect sun, and open on summer nights to radiate heat to the sky.

Another variation on high-mass cooling depends upon earth contact. The earth acts as a heat sink, keeping walls and floors (even roofs when earth-covered) cool. However, if the earth is allowed to continue to act as a heat sink in winter, heating needs could be greatly increased. Thus, a strategy for summer contact and winter isolation might be appropriate.

(c) High-Mass Cooling with Night Ventilation

This hot-dry summer design strategy must use outdoor air at subcomfortable nighttime temperatures to flush away heat stored during the daytime. The fewer the subcomfortable night hours, the greater the area of thermally massive surface that must be provided to store the day's heat. Also, because there are more hours of daylight and fewer of nighttime, the ventilation must occur quickly and thoroughly, probably using fans. (Nightly wind velocities are typically lower than daytime velocities, because summer wind is often driven by regional solar overheating of the ground.) The building switches from a thermally closed condition by day (to exclude sun and hot outdoor air) to an open condition at night (to allow ventilation to cool the mass). Note: Nighttime temperatures must be cooler than the comfort zone temperature if this strategy is to be effective. Figure 10.4 shows the need to inspect both ends of the typical day's bioclimatic plot for this strategy.

This cooling strategy is highly compatible with passive solar heating strategies that rely on large areas of thermal mass, such as *direct gain*. It is suitable for large, high buildings, particularly those that have concrete (thermally massive) structural systems.

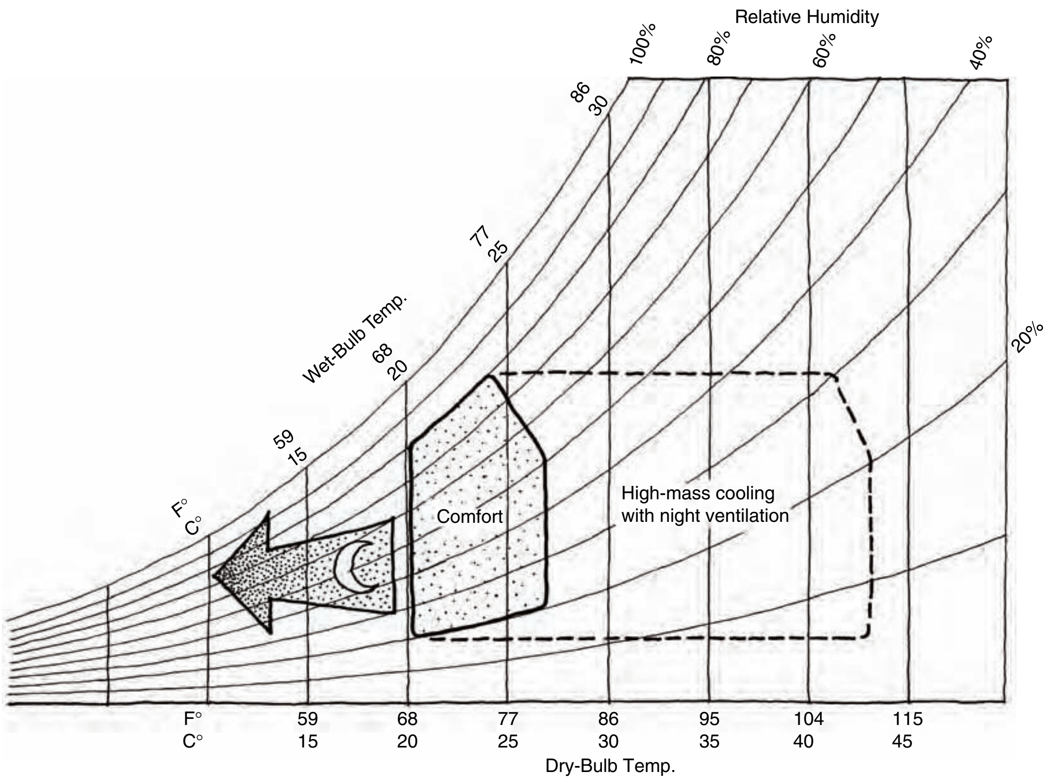


Fig. 10.4 *Strategy chart segment for night ventilation of thermal mass. This strategy is most successful when cool nighttime temperatures are available, preferably below comfort zone temperatures for several hours.*

(d) Evaporative Cooling

This design strategy relies on the principle that when moisture is added to air, relative humidity increases while dry-bulb temperature decreases. (On the bioclimatic chart, this pattern exactly follows the constant wet-bulb line, upward and to the left.) In conditions that are more uncomfortably dry than uncomfortably hot, lower air temperature in exchange for higher humidity is a win-win proposition. However, large quantities of both water and outdoor air are needed; fan-driven evaporative coolers are the most common way to provide this kind of cooling.

Evaporative cooling imposes few constraints on designers because the equipment resembles conventional HVAC systems. Rather high indoor air velocities and their associated sounds are typical of these systems, and the aroma of the wetted material of the cooler is often noticeable. The coolest air will be in the vicinity of the air inlet to the space, the warmest air at the outlet from the space.

10.3 SUMMER HEAT GAIN GUIDELINES

Estimating the extent of the heat gains in a building is the first step to designing a passive cooling approach. Passive cooling guidelines and calculations are expressed in heat to be removed per unit of floor area, so it is necessary to gather data and building information to do the calculations. Sometimes cooling loads are more closely related to individual building characteristics than to climate; for example, sunshading and internal heat gains are particularly influential on cooling loads. An underlying assumption in all passive design and energy performance calculations is optimization of the building envelope to minimize heat gains. A comparison of these guidelines with more detailed analysis procedures is given in Table 10.2.

Note that "open" buildings, such as those that are naturally ventilated, do not have heat gains from infiltration, because they are assumed to maintain

TABLE 10.2 Comparing Passive Cooling Design Guidelines with Detailed Calculation Procedures

Design Guidelines (Section 10.4)	Detailed Calculations (Section 10.8)
PART A. CROSS-VENTILATION	
• Assume 3F° [1.6C°] Δt • Assume window is oriented to wind	• Use actual Δt • Use actual window orientation to wind
PART B. STACK VENTILATION	
• Assume 3F° (1.6C°) Δt	• Use actual Δt
PART C. NIGHT VENTILATION OF THERMAL MASS	
• Assume ratio of mass area/floor area • Assume cooling during hour of maximum Δt • Assume maximum Δt for natural ventilation estimation • Find total cooling and required air flow rate	• Use actual exposed mass area • Use actual mass heat capacity • Use actual hourly chart of air and mass temperatures
PART D. EVAPORATIVE COOLING (ACTIVE)	
• Assume 2.67 cfm/ft^2 floor area (13.6 L/s m^2) • Assume 83°F (28.3°C) exhaust air • Find allowable Δt as air passes through indoors • Then cfm = (Btu/h)/(1.1)(Δt) [L/s = W/(1.2)(Δt)]	• Use actual outdoor temperature for analysis • Determine actual indoor air temperature
PART E. COOLTOWERS (PASSIVE, EVAPORATIVE)	
• Find approximate exit air temperature • Find approximate flow rate • Then Btu/h = (cfm)(1.1)(Δt) [W = (L/s)(1.2)(Δt)]	• Use actual outdoor temperature and wet-bulb depression • Find actual exit air (supply) temperature • Find actual exit airflow rate • Then Btu/h = (cfm)(1.1)(Δt) [W = (L/s)(1.2)(Δt)]
PART F. ROOF PONDS	
• Assume pond maximum temperature of 80°F (26.7°C) • Estimate pond minimum temperature • Assume 30% gain through roof insulation • Assume pond depth from 3 in. to 6 in. (75–150 mm) • Find pond depth and area	• Use actual outdoor temperature, resulting pond temperature • Use actual heat gain through roof insulation • Consider actual hours of internal heat gains • Find pond depth and area • Determine size of backup cooling
PART G. EARTH TUBES	
• Assume 65°F (18.3°C) soil temperature • Assume soil conductivity • Does not specify depth • Assume 85°F (29.4°C) outdoor air • Assume 500 fpm (2.5 m/s) velocity • Choose diameter and length to match cooling load	• Actual underground temperature; assume resulting tube temperature is within 4F° (2.2 C°) • Actual soil conductivity • Actual depth • Actual outdoor air temperature • Assume 500 fpm (2.5 m/s) velocity • Calculate actual cooling capacity

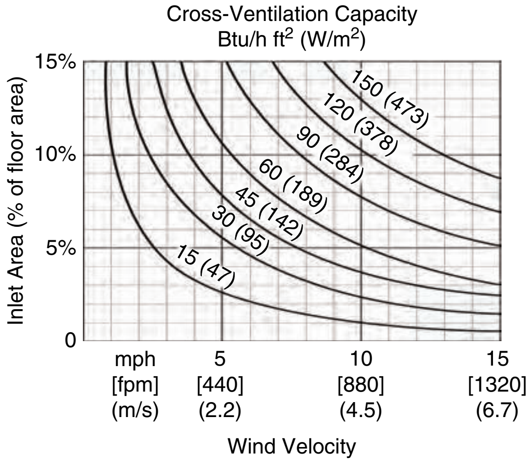
internal temperatures that are slightly *above* exterior temperatures. However, these buildings do experience heat gains through windows, walls, and roofs due to solar impacts on these surfaces. For "closed" buildings, heat gain from infiltration or ventilation must be added, because these structures maintain internal temperatures lower than outside temperatures.

10.4 PASSIVE COOLING GUIDELINES

The design guidelines for passive cooling are much newer and less tested than those for passive heating. It is important to *first* check the match between the climate and the cooling strategy, as was done earlier in this chapter, before applying these guidelines to a building design.

(a) Cross-Ventilation

One of the oldest cooling methods known, this strategy provides plentiful fresh air but maintains a building at temperatures slightly *above* those outdoors. The cross-ventilation inlet (window) areas, expressed as percentage of total floor area, are related to wind speed and resulting heat removal in Fig. 10.5. Remember that *an equal* (*or greater*) *area of outlet openings* must also be provided. Furthermore, any internal obstructions (such as partitions) must have a total area of openings at least equal to this required inlet area. The assumptions about wind direction and indoor–outdoor temperature differences that were used to produce these guidelines are explained in the figure. For more detailed wind speed and direction information, see Section 10.8.



Interactive Animation

Fig. 10.5 *Cross-ventilation design guidelines for heat removed per unit floor area and relationship of inlet openings and wind speed. The total inlet opening area is expressed as a percentage of the total floor area served by cross-ventilation. Note: Outlet areas must be at least equal to inlet areas. This graph is based on an internal temperature 3F° (1.7C°) above the exterior temperature and assumes that the wind is not quite perpendicular to the window openings, for a wind effectiveness factor of 0.4 (see Section 10.8). (Drawn by Tyler Mavichien.)*

The Δt of 3F° (1.6C°) used in Fig. 10.5 is deliberately kept small to encourage open strategies in milder summer climates. Thus, an interior temperature of 83°F (28.3°C), which is comfortable with sufficient air motion, lower RH, and comfortable surface temperatures, would be obtainable with an outside temperature of 80°F (26.7°C). However, a greater Δt is often appropriate—for example, for spring or fall cooling of office buildings, or for summer cooling of factories or kitchens where internal temperatures may remain in the low 90s (+/− 32°C). In such cases, find the percentage of inlet area required; then multiply by the ratio

$$\frac{3\text{F}° \text{ (or } 1.6\text{C}°)}{\text{actual } \Delta t}$$

to obtain required cross-ventilation areas for any specific temperature difference.

(b) Stack Ventilation

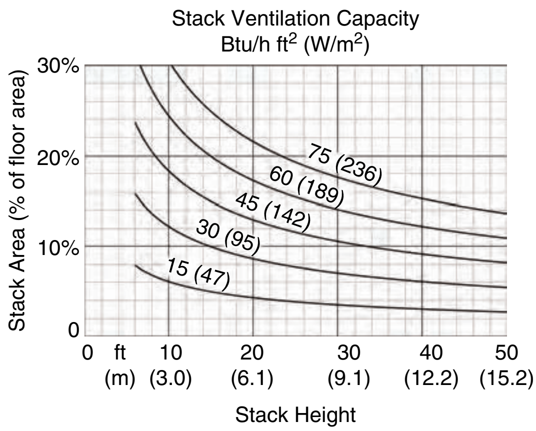
This is another historically useful strategy, which, like cross-ventilation, provides plentiful fresh air but maintains a building at temperatures slightly *above* outdoor temperatures. The stack inlet areas, expressed as percentage of total floor area, are related to stack height and the resulting heat removal in Fig. 10.6. Remember that *an equal (or greater) area of stack outlet openings, as well as at least an equal cross-sectional area through the vertical stack*, is also required. Again, consider internal obstructions: partitions must have a total of openings at least equal to this required inlet area. The assumptions about indoor–outdoor temperature differences that were used to produce this guideline are explained in the figure.

Adjustment of the Δt for this guideline is similar to the procedure for cross-ventilation. It requires multiplication of the required percentage of stack area by the ratio

$$\frac{3\text{F}° \text{ (or } 1.6\text{C}°)}{\text{actual } \Delta t}$$

to obtain the required stack ventilation areas for any other specific temperature difference.

Until the advent of air conditioning, these methods of cross- and stack ventilation were used in virtually all commercial buildings. In some climates with mild summers, newer buildings are turning to these older methods. Figure 10.7 shows the Thoreau Center for Sustainability in San Francisco's Presidio National Park. An older military hospital was renovated for offices for nonprofit environmental organizations. To maximize daylighting and passive



Interactive Animation

Fig. 10.6 *Stack ventilation design guidelines for heat removed per unit floor area and the relationship of stack height and inlet openings. The area of stack inlet/throat/outlet is expressed as a percentage of the total floor area served by stack ventilation. Note: Outlet areas and the stack throat area must be at least equal to inlet areas. This graph is based on an internal temperature of 83°F and an exterior temperature 80°F, for a 3F° differential (28.3°C internal, 26.7°C external, for a 1.6C° differential). (Drawn by Sara Tepfer; © Walter Grondzik and Alison Kwok; all rights reserved.)*

cooling, the original operable windows are utilized. Interior partitions are kept low enough to facilitate cross-ventilation, with integral indirect electric lighting using the high white ceiling. The section indicates that both cross-ventilation and stack effect are anticipated. However, the stack openings to the attic and, subsequently, through the roof are less than 1% of the total floor area. The most likely benefit of the stack effect here is to keep the attic at cooler summer temperatures (with air drawn in at the eave vents, not flowing outward as shown).

(c) Night Ventilation of Thermal Mass

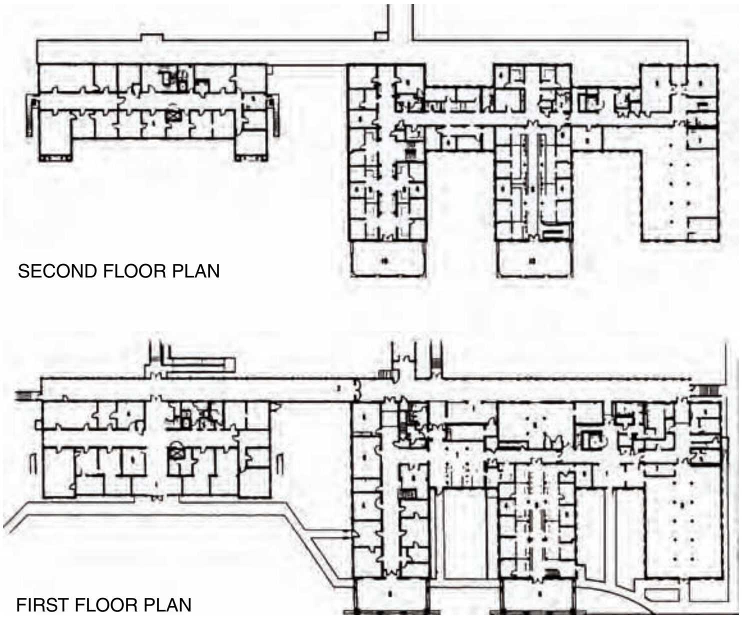
This strategy maintains a building at temperatures lower than those outside by day and flushes the building with plentiful fresh air by night. The sizing procedure is shown in Fig. 10.8, where climate data are related to two representative types of thermally massive building. For each type, the graphs show the *daily* Btu per square foot of floor area that can be stored. The "average" mass building is represented by a building with an exposed concrete floor 4 in. (100 mm) thick (or an exposed ceiling of equivalent construction). There is one unit area of exposed mass for each unit floor area. The "high" mass building is similar to the typical passively solar-heated, direct-gain building or to a multistory building with an exposed concrete structure, in which *both sides* of the floor slab are available for thermal storage, or an equivalent exposed mass area in walls, and so on. For this building, there are two units of exposed mass for each unit of floor area.

The climate data needed for Fig. 10.8 (maximum summer design DB temperature and mean daily range) are given in Appendices B.1 through B.5. These data also allow calculation of the *minimum* summer design DB temperature; that is, maximum design DB temperature minus mean daily range. This minimum temperature is of interest here because the thermal mass of the building will be lowered toward (but not quite to) it during night ventilation. For high daily range climates, the lowest temperature obtained by the thermal mass will

(*a*)

Interactive Animation

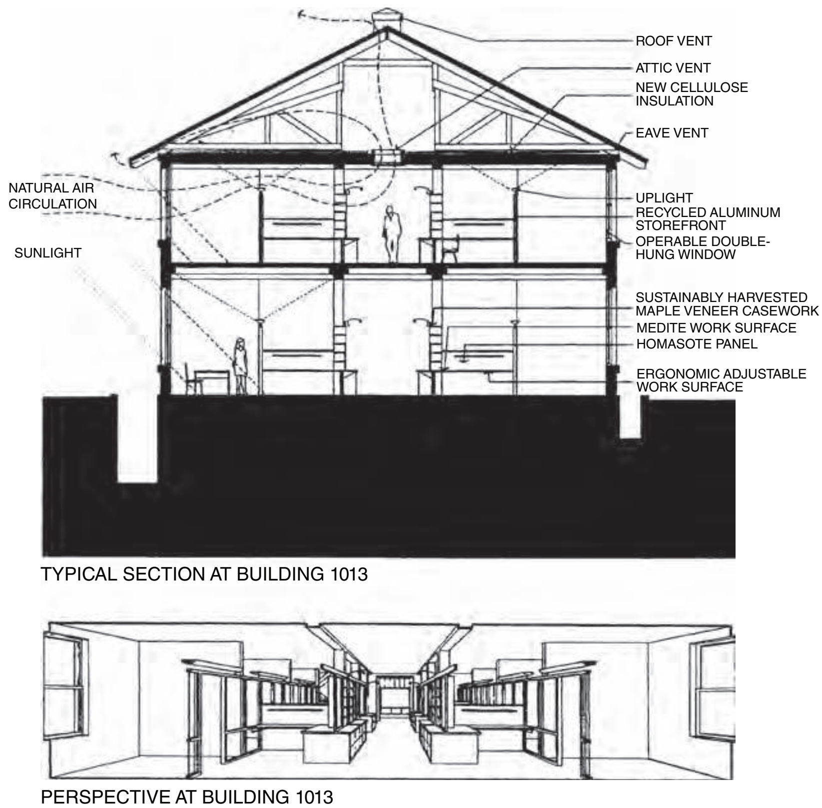
Fig. 10.7 *The Thoreau Center for Sustainability occupies renovated hospital buildings (a) in San Francisco's Presidio National Park. (b) Relatively narrow floor plans facilitate daylighting and natural ventilation. (c) Interior at the center corridor. (d) Section illustrates daylighting and cross-ventilation. Very small stack openings relative to the floor area served limit the stack effect to a minor role. (Drawings courtesy of Tanner Leddy Maytum Stacy Architects, San Francisco.)*



(*b*)

(*c*)

Fig. 10.7 *(Continued)*



(*d*)

Fig. 10.7 *(Continued)*

be *about one-fourth of the mean daily range above the minimum air temperature* (for lower daily range climates—30F° (16.7C°) or less—*one-fifth* of the mean daily range).

EXAMPLE 10.2 Compare the potential for night ventilation of mass in Sacramento, California, and Oklahoma City, Oklahoma.

SOLUTION

Sacramento, California:

Highest DB = 94.8°F (Table B.1); (34.9°C Table B.3)
Mean daily range = 31.9F° (Table B.1); (17.7C° Table B.3)
Lowest DB = 94.8 – 31.9 = 62.9°F (17.2°C)

Approximate lowest mass temperature: ¼ of 31.9 = 8F°; 63 + 8 = 71°F (21.6°C)

Oklahoma City, Oklahoma:

Highest DB = 94.5°F (34.7°C)
Mean daily range = 19.9F° (-11.1°C)
Lowest DB = 95 – 19.9 = 75.1°F (23.9°C)

Approximate lowest mass temperature: 1/5 of 19.9 = 4F°; 75 + 4 = 79°F (26.1°C)

From these data, it appears that Sacramento, with a comfortably low 71°F (21.6°C) mass temperature, is a likely site for night ventilation to remove heat stored in the building's mass. However, Oklahoma City's 79°F (26.1°C) lowest mass temperature is at the middle of the comfort zone, suggesting a climate in which this passive strategy will be harder to achieve. In either location, performance studies can best be carried out with the details of this mass cooling procedure, found in Section 10.8.

We can also compare the daily heat removed. For a high-mass building, from Fig. 10.8*b*:

Sacramento (DB = 94.8°F, MDR = 31.9F°) storage is somewhat more than 100 Btu/ft^2 (315 W/m^2) day.

Oklahoma City (DB = 94.5°F, MDR = 19.9F°) storage is much less than 80 Btu/ft^2 (252 W/m^2) day. ■

Before this information can be fully utilized, the number of hours for which the building must be

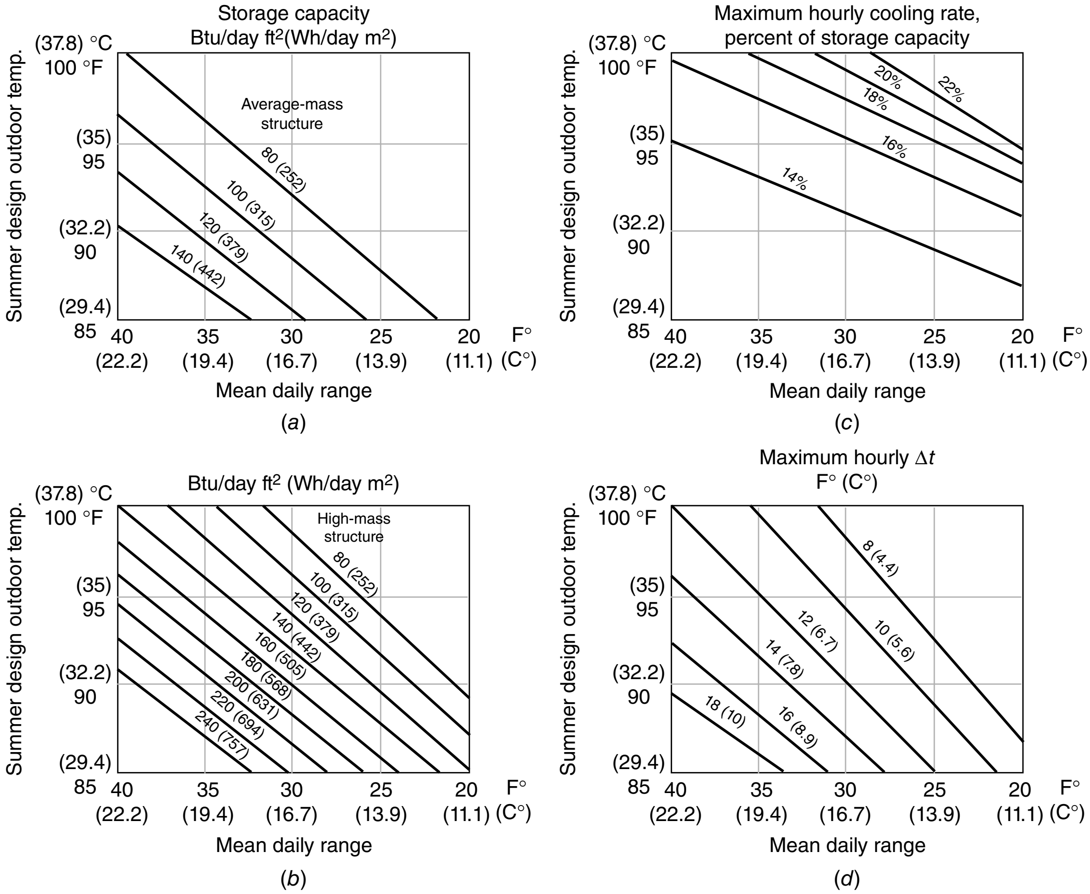


Fig. 10.8 *Night ventilation of thermal mass design guidelines. Parts (a) and (b) show Btu/day stored and removed per ft² of floor area (W/day per m² of floor area). Enter these graphs with your location's summer design outdoor DB temperature and the MDR (mean daily range). (a) "Average mass" structure has unit area of mass surface exposed per unit area of floor area, where the mass is a 4-in. (100-mm) ordinary-density concrete slab. (b) "High-mass structure" has two unit areas of mass surface exposed per unit area of floor area, where the mass is a 3-in. (75-mm) ordinary-density concrete slab (or both sides of a 6-in. [150-mm] concrete wall or slab exposed). Both average- and high-mass structures go into "open" mode when the outdoor temperature drops below 80°F (26.7°C); therefore, the highest mass temperature is assumed to be 80°F (26.7°C). Part (c) shows the approximate percentage of the daily total heat stored that is removed during the nighttime hour of maximum cooling. Part (d) shows the Δt between the outdoor air and inside mass that exists during that hour of maximum cooling. Required ventilation rates can then be determined from (c) and (d).*

"closed" must be determined. During these hours, heat will be stored in the structure, up to the maximum storage indicated in Fig. 10.8. Typically, these buildings will go into the thermally closed mode (allowing minimum ventilation only) at about 6:00 A.M. for a day with 100°F (37.8°C) maximum or about 8:00 A.M. for a day with 85°F (29.4°C) maximum, remaining in the closed mode until the outdoor temperature drops below 80°F (26.7°C). (To approximate this hour, assume that the midpoint outdoor temperature, between daily high and daily low, occurs at around 10:00 P.M.) Thus, the typical office building remains thermally closed during the 8 or 9 hours of summer occupancy. All the heat generated during the closed mode—8 to 9 daytime hours—must be stored in the structure:

Heat to be stored per ft^2 (or m^2) of floor area
= hours occupied in closed mode
× heat gain, Btu/h ft^2 (or W/m^2) of floor area (from Table G.3)

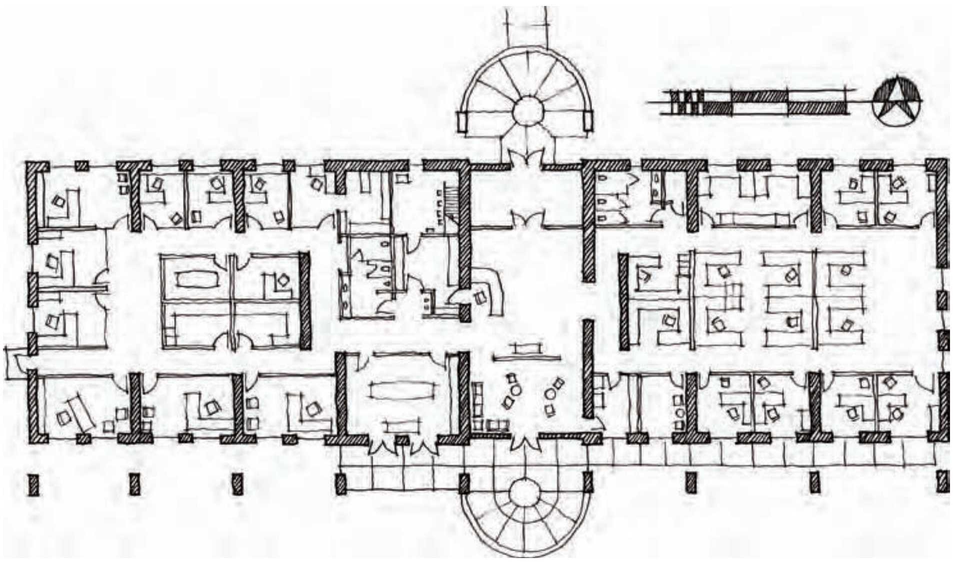
Having found the amount of heat that can be stored each day, the designer must then solve the problem of removing the heat by night. Either natural or forced ventilation can be used, but in many locations wind speed is very low on summer nights.

The ventilation rate is determined by the "best hour" of cooling during the night, that is, the hour during which the temperature difference, Δt, between inside mass and outdoor air is greatest, and hence the most heat is removed. This "best hour" information can be found in Fig. 10.8*c* and Fig. 10.8*d*. Then the cross- or stack ventilation rules of thumb can be used to size the openings.

See Table 10.2 for a comparison of these guidelines and more detailed calculation procedures for night ventilation of thermal mass.

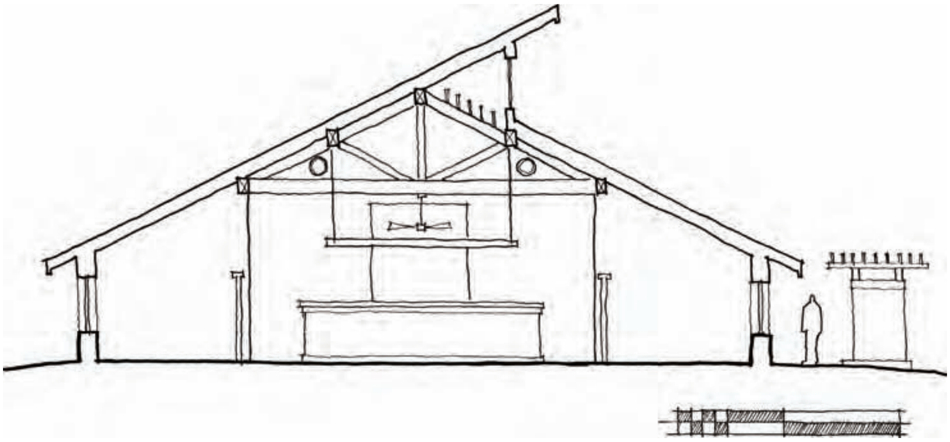
The administration building for the Fetzer Winery sits among grapevines in northern California's Mendocino Valley (Fig. 10.9). The summer design condition is approximately 96/68, with MDR 30F° (35.6/20, MDR 16.7C°). As an

(*a*)



(*b*)

Fig. 10.9 *The Fetzer Winery administration building (a) in its rural Mendocino County, California, setting. The south-facing clerestory and a deciduous vine and trellis are the more visible parts of the daylighting, passive solar heating, and passive cooling strategies. (b) Plan shows the relation of workstations to north and south daylight. (c) Section with ducts for the night air flush as well as for conventional heating and cooling. (d) North-side dormers are for night air intake and exhaust. (Parts* b *and* c *redrawn by Dain Carlson from original drawings provided courtesy of Valley Architects, St. Helena, CA.)*



(*c*)

(*d*)

Fig. 10.9 *(Continued)*

average-mass structure, this building could store and remove about 60 Btu/ft^2 day (190 W/m^2 day); as a high-mass structure, it could store and remove about 100 Btu/ft^2 day (315 W/m^2 day).

(d) Evaporative Cooling

The most common evaporative cooler is not strictly passive cooling, because it depends on a fan to force large quantities of outdoor air through a wet filter, thereby lowering the air temperature and raising the relative humidity before delivering the air to the space to be cooled. In hot and arid climates, the energy used by the fan in evaporative systems is less than the energy needed to achieve compression-refrigeration cooling. Although this process requires water, it does not use refrigerants that may pose a threat to the Earth's environment.

Before using the following guidelines, be sure to check the cooling strategy chart (Fig. 10.2) to determine whether evaporative cooling is appropriate for your climate. It is unlikely that evaporative cooling will be helpful in the humid Southeastern United States.

The rates of evaporative cooling presented in Fig. 10.10 are based upon a rather high airflow

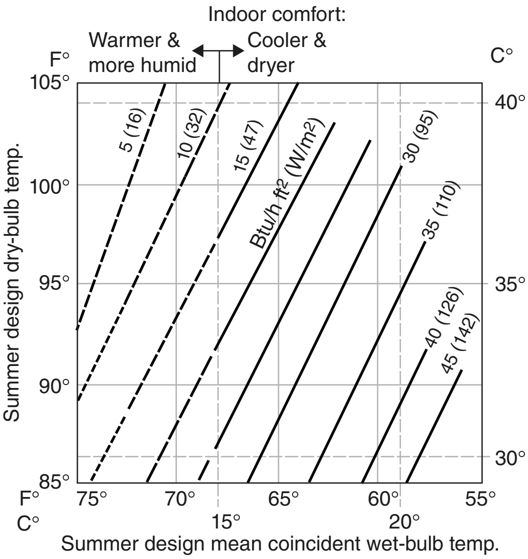


Fig. 10.10 *Fan-forced evaporative cooling design guideline for Btu/h removed per ft² of floor area (W per m²). A forced airflow rate of 2.67 cfm per ft² of floor area (13.56 L/s per m² of floor area) is assumed, as is an exiting (exhaust) air temperature of 83°F (28.3°C). The dashed lines toward the left side of the graph represent increasingly humid indoor air, which may cause discomfort.*

of 2.67 cfm per ft^2 of floor area (13.56 L/s m^2). (In conventional cooling, an airflow rate closer to 1 cfm per ft^2 (5 L/s m^2) is more common.) With this amount of air motion, a highest indoor air temperature of 83°F (28.3°C) is assumed; so the evaporatively cooled air, after absorbing the heat from the space, exits at 83°F (28.3°C). (Note: This may still be well below the outdoor temperature—might it do some useful cooling?) To use Fig. 10.10, first find in Table B.1 the summer design DB and mean coincident WB temperatures for your location. Enter the graph at these two data points, and at their intersection find the approximate amount of heat in Btu/h ft^2 (W/m^2) that evaporative cooling can remove. As WB temperatures surpass 68°F (20.0°C) (represented by dotted lines in the graph), indoor conditions become increasingly humid, producing almost certain discomfort with an indoor WB temperature of 75°F (23.9°C).

A more thorough method for evaluating evaporative cooling potential is presented in Section 10.8, where various airflow rates and temperatures of supply air and exit air can be examined. See Table 10.2 for a comparison of this guideline and the more thorough method.

EXAMPLE 10.3 Evaluate the potential for evaporative cooling for a 3000-ft^2 (279 m^2) retail store in Denver, Colorado. Because of large electric lighting and equipment display loads, the approximate heat gain is 30 Btu/h ft^2 (95 W/m^2).

SOLUTION

From Table B.1, Denver has a summer design DB temperature of 88°F (33.1°C), with a coincident WB temperature of 59.6°F (15.3°C). Checking back with Fig. 10.2, these design conditions fall well within the climate served by evaporative cooling. Next, enter Fig. 10.10 at the points of 88°F (33.1°C) DB and 59.6°F (15.3°C) WB; the intersection of these data lines shows that under such conditions, heat gains can be removed by evaporative cooling at a rate of about 37 Btu/h ft^2 of floor area.

40 Btu/h ft^2 (126 W/m^2) capacity
> 30 Btu/h ft^2 (95 W/m^2) approximate heat gains

Therefore, evaporative coolers can meet the need. Because Fig. 10.10 assumes an airflow rate of 2.67 cfm per ft^2 (13.56 L/s per m^2), the cooler's approximate size will be

$$3000\text{ ft}^2 \times 2.67\text{ cfm/ft}^2 = 8000\text{ cfm }(279\text{ m}^2 \times 13.56 = 3780\text{ L/s})$$

The evaporative cooler size could be reduced by the ratio of cooling capacity to needed heat removal:

$$8000\text{ cfm} \times \frac{30\text{ Btu/h ft}^2\text{ need}}{40\text{ Btu/h ft}^2\text{ capacity}}$$

$$= \text{about 6000 cfm (corresponding to 2835 L/s)}$$

Sticking with the larger capacity unit, however, will allow for a lower indoor air exit temperature than the 83°F (28.3°C) assumed in Fig. 10.10, so the larger capacity is a safer approximation. ■

(e) Cooltowers

A more passive approach to evaporative cooling appears as a tower on the residence in Fig. 10.11. This University of Arizona experimental building near the Tucson Airport has a *cooltower* with wetted pads on all four faces at the top. Hot, dry air is cooled as it passes through the pads, dropping to the base of the tower and then into the house. Analysis by Givoni (1994) indicates that such a tower's delivery of wetter, cooler air is almost independent of

Fig. 10.11 *An experimental residence in Tucson, Arizona, is passively and evaporatively cooled by a cooltower (at the right in the photograph). Hot, dry air passes through the wetted pads at the tower's top and undergoes a drop in DB temperature that causes it to fall, entering the residence at the bottom of the tower. The tower at the left is a solar chimney to help increase the flow of warmed exhaust air.*

wind speed and also is not dependent on the second tower at the opposite end of this building, a *solar chimney* through which air from the house is discharged. Temperature and flow rate of air delivered to a building by a passive cool tower can be approximated from Fig. 10.12, but such data are based on very little experimental work. A well-regarded building using this principle, as well as Trombe wall passive solar heating, is the Zion National Park Visitor Center (Fig. 10.13).

EXAMPLE 10.4 A 3000-ft^2 (279-m^2) retail store in Las Vegas, Nevada, has a summer heat gain of 14 Btu/h ft^2 (44.2 W/m^2). How tall should a passive cool tower be to provide the needed cooling under summer design conditions?

SOLUTION

From Table B.1, Las Vegas has a summer DB = 103.7°F (39.8°C) with a mean coincident WB = 65.5°F (18.6°C). This represents a *wet-bulb depression* (DB – WB) of 41F° (21.2C°). From Fig. 10.12*a*, at 103.7°F DB and 38F° (DB – WB), the air exiting a passive cool tower will be about 70°F (21°C).

Next, determine the amount of supply air at 70°F needed to maintain this building at an indoor temperature of 82°F (27.8°C) (probably a reasonable indoor temperature when it is 104°F outdoors, given the air motion provided by this passive cool tower).

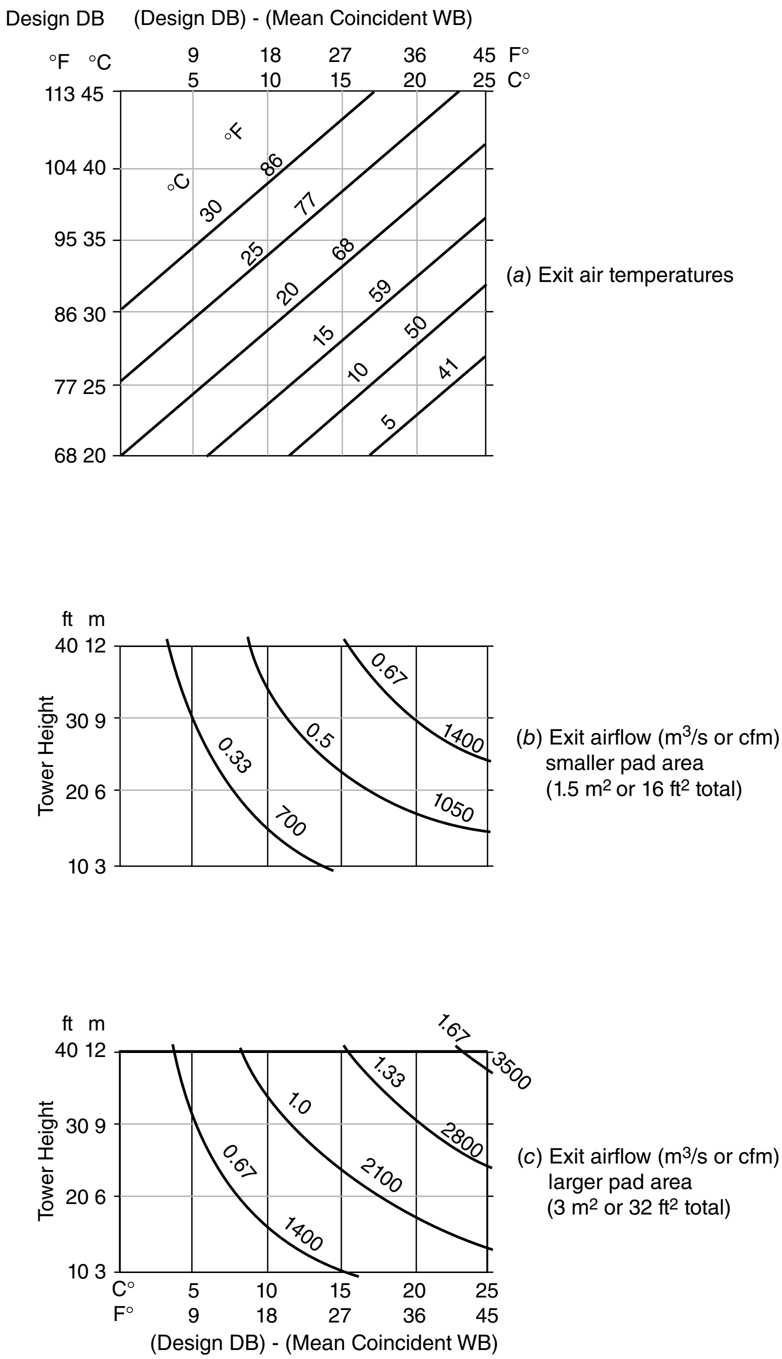
$$\begin{aligned} \text{cfm} &= (\text{Btu/h})/(1.1)(\Delta t) \\ &= (3000\ \text{ft}^2 \times 14\ \text{Btu/h ft}^2)/(1.1)(82-70) \\ &= \text{about } 3200\ \text{cfm} \end{aligned}$$

At the Las Vegas design condition of 103.7 DB, 38F° DB – WB, from Fig. 10.12*c*, it appears that a cool tower of 40 ft (12 m) in height, with a total wetted pad area of 32 ft^2 (3 m^2), will provide about 3300 cfm (1558 L/s), somewhat more than the minimum just calculated. ■

(f) Roof Ponds

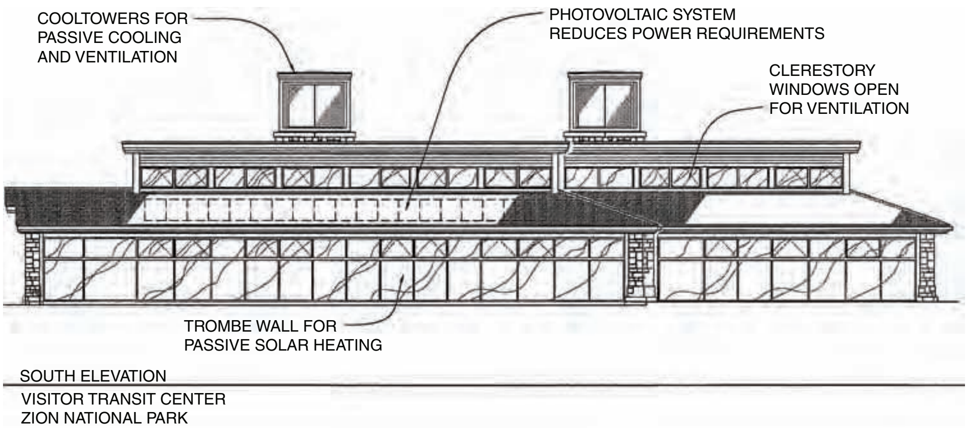
Roof ponds are a promising strategy that has rarely been implemented, possibly due to water phobia among architects and clients alike. Yet roof ponds demonstrate the most stable interior temperatures of any of these techniques, needing electricity only to open and close the sliding insulation panels on the roof. Roof ponds sized for cooling will likely be nearly equal in area to the floors of the buildings they cool. Average pond depth is between 3 and 6 in. (75 and 150 mm). A more detailed and precise procedure for determining pond area is presented in Section 10.8, but here is a quick approximation to size roof pond areas:

- Set pond maximum temperature: 80°F (26.7°C); this temperature is based upon the assumption that any higher pond temperature would fail to produce cooling for the building interior
- Assume pond minimum temperature is the minimum nighttime DB air temperature; = maximum daytime temperature – mean daily range (from Table B.1)
- Establish pond Δt; = pond maximum temperature – pond minimum temperature
- Estimate allowable daily building heat that can be stored in pond; Btu/day ft^2 (kWh/day m^2) = (0.7)

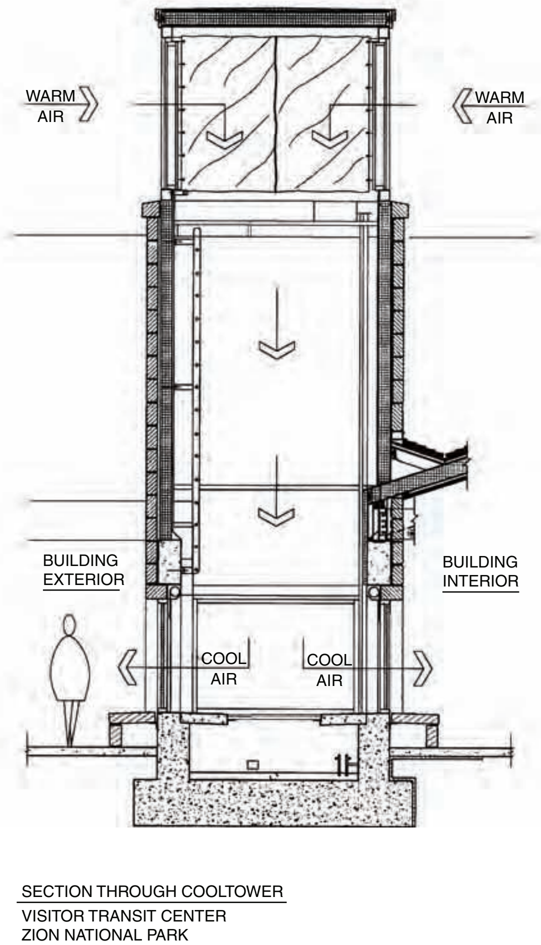


Interactive Animation

Fig. 10.12 *Design guidelines for cooltowers. (a) The temperature of the air as it leaves the cooltower (enters the building) depends on the outdoor DB temperature, as well as the difference between the DB and WB temperatures. The flow rate of the exit air depends on the tower height, as well as the difference between the DB and WB temperatures. (b) Flow rate for a smaller area of wetted pads, 1.5 m2 (16 ft²). (c) Flow rate for a larger area of wetted pads, 3 m² (32 ft²). (Based upon the work of Givoni, 1994.)*

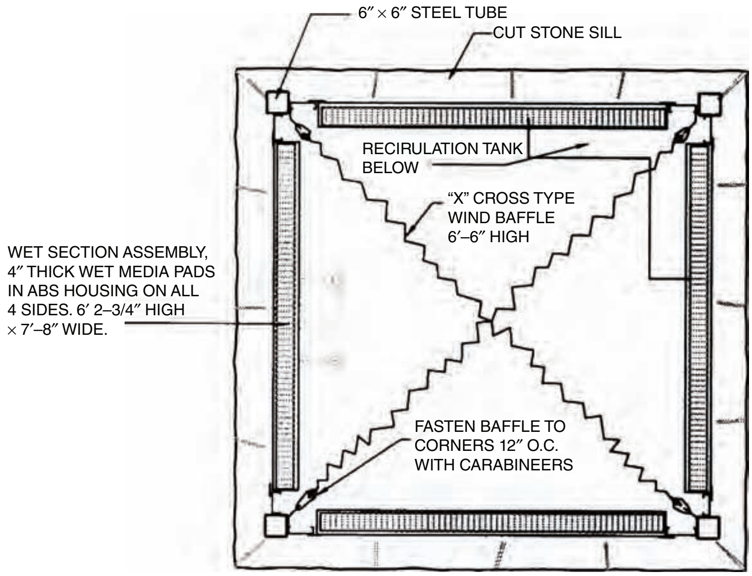


(*a*)



(*b*)

Fig. 10.13 *The Visitor Center at Zion National Park (Utah) features both cooling by cooltowers and solar heating (a) by Trombe walls and a clerestory. Because many of the building's functions can be performed outside, each cooltower (b) has both an indoor and an outdoor outlet, either of which can be closed off when not needed. Air enters through wet media pads at the top of the tower (c). An X-baffle then diverts the air downward. The building also features photovoltaics (PV) and water harvesting. (Courtesy of The National Park Service, Denver Service Center.)*



(*c*)

Fig. 10.13 *(Continued)*

(pond Δt, F°) (pond depth, ft) (62.5 lb/ft^3 water) (1.0 Btu/lb °F), with depth not to exceed 0.75 ft (0.23 m) and assuming that 70% of the pond's daily heat gain is from the building below and 30% is through the insulated panels above the pond (in SI units, this relationship is: (0.7) (pond Δt, C°) (pond depth, m) (1000 kg/m^3) (4.18 kJ/kg K)

- Determine required "size" of pond (ft^2 [m^2] of pond per ft^2 [m^2] of floor area)

$$= \frac{\text{building sensible heat gain per day}}{\text{pond allowable heat stored per day}}$$

See Table 10.2 for a comparison of the design guideline and the more detailed calculations for roof ponds.

EXAMPLE 10.5 An office building in Albuquerque, New Mexico, is to be cooled by a roof pond 4 in. (100 mm) deep. An hourly heat gain of 15 Btu/h ft^2 (47 W/m^2) is assumed (excluding heat gain through the roof).

SOLUTION

For Albuquerque:

Maximum temperature = 91°F (Table B.1); (32.8°C Table B.3)

Mean daily range = 25.3F° (Table B.1); (14.1C° Table B.3)

Minimum (night) temperature = 91 − 25.3 = 65.7°F (18.7°C)

Therefore:

Pond Δt = 80°F (26.7°C) maximum − 65.7°F (18.7°C) minimum = 14.3F° (8.0C°)

Pond storage capacity for building heat
= 0.7(14.3°)(0.33 ft)(62.5 lb/ft^3)(1 Btu/lb °F)
= 206 Btu/day ft^2 ([0.7][8.0C°][0.1 m][1000 kg/m^3][4.18 kJ/kg K] = 650 kJ/day m^2 and 650 kJ/day m^2/0.278 = 2338 Wh/day m^2)

The required pond size, then, is

$$\frac{15\ \text{Btu/h ft}^2 \times 9\ \text{h/day}}{206\ \text{Btu/day ft}^2} = 0.66\ \text{ft}^2/\text{ft}^2\ \text{floor area}\ (0.66\ \text{m}^2/\text{m}^2)$$

Therefore, a 4-in. (100-mm) pond covering 72% of the one-story building's floor area will be approximately large enough to cool the building. (If the entire ceiling is desirable as a cooled surface, then a slightly shallower pond of greater area could be used. However, the sliding insulation panels must be stacked somewhere beyond the edge of the roof pond.)

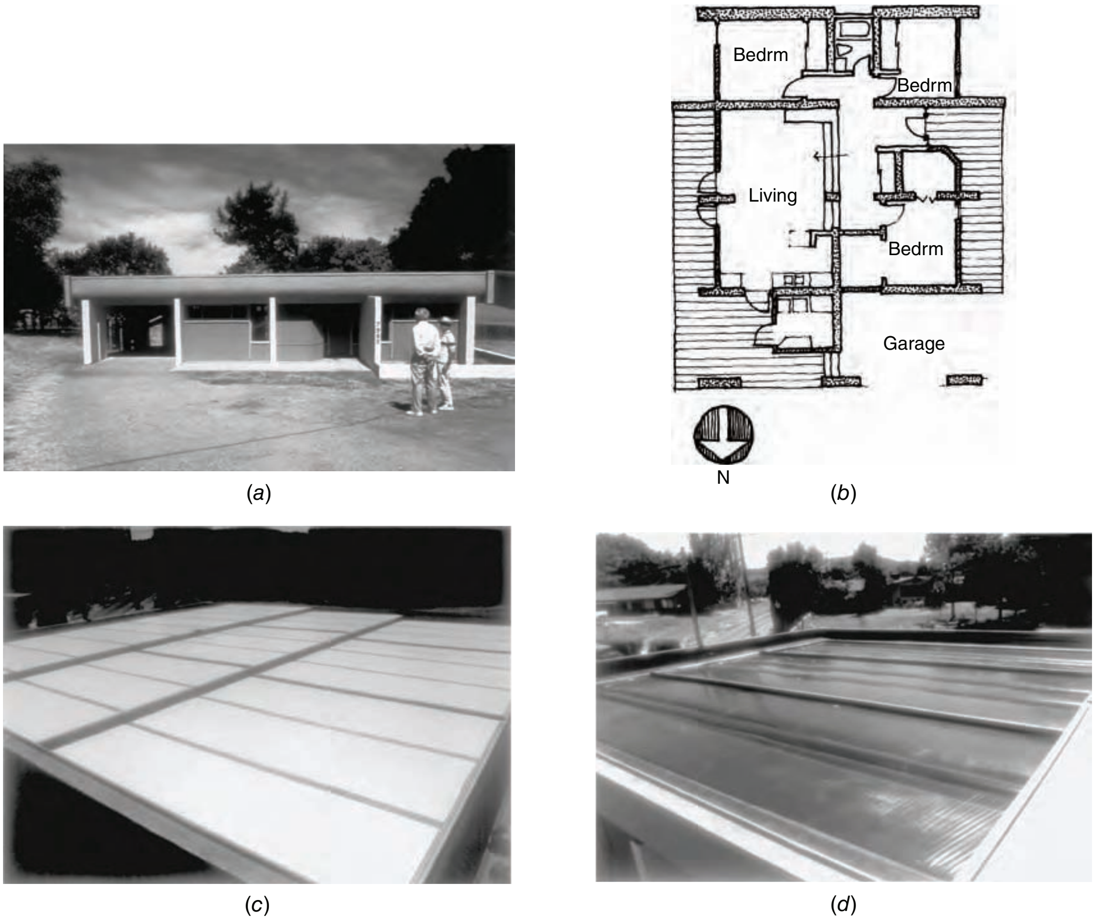
We revisit this building as Example 10.10, in Section 10.8. ■

The residence in Fig. 10.14 is one of the first roof pond structures. Located in Atascadero, California, at about 35°N latitude, it has a remarkable history of thermal stability, providing both passive solar heating in winter and passive cooling in summer. Roof pond inventor Harold Hay donated the building to California State Polytechnic at San Luis Obispo in the late 1990s. To emphasize the pond as the solar heating device, this house has almost no south-facing glass (most windows face east toward a small lake). The sliding insulation panels are stacked when open (by day in winter, by night in summer) over the carport on the north end of the building.

(g) Earth Tubes

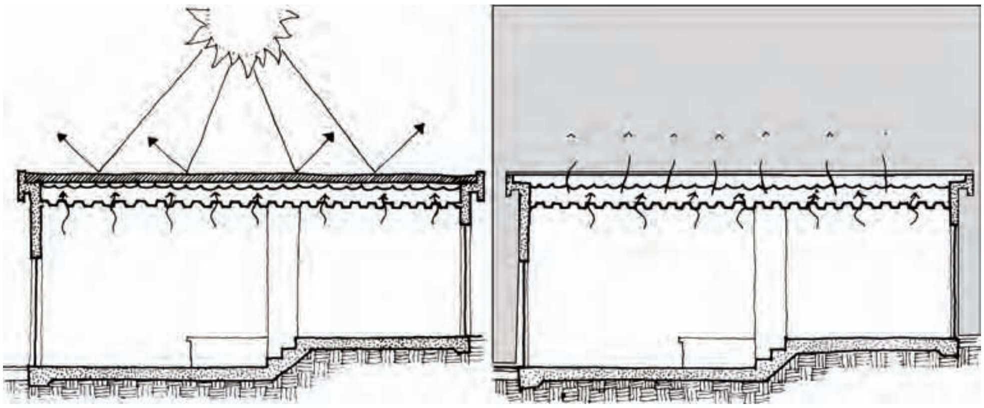
These provide a way to cool outdoor air before it enters a building. A fan is used to force sufficient quantities of air through these long tubes. Because earth tubes need to be well underground as well as rather long in order to cool outdoor air, it is rarely economical to install enough earth tubes to completely meet a building's need for cooling. If long trenches are needed for another purpose (underground water lines, for example), an earth tube is more feasible. Where earth tubes are considered, the component of building heat gain that is represented by cooling fresh air (Table G.3, Part E) can sometimes be mitigated using this strategy.

The estimate of cooling for the earth tubes described in Fig. 10.15 is based on Abrams (1986),



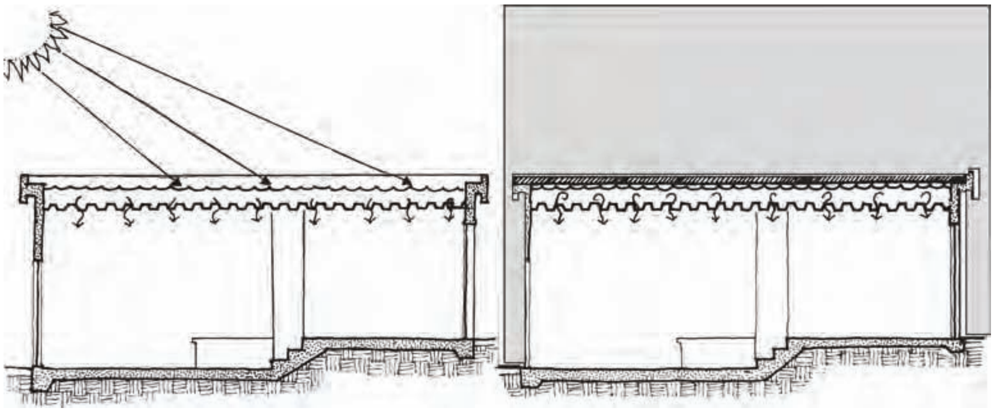
Interactive Animation

Fig. 10.14 *One of the first roof pond buildings, this Atascadero, California, residence is now a research building for California State Polytechnic University at San Luis Obispo. (a) The exterior from the west. (b) Plan. South exposure is minimal; the roof is the surface of interest for heating and cooling. (c) The roof insulating panels in the closed position (as on a summer day). (d) The roof insulating panels in the open position (as on a summer night). Water is contained within plastic bags laid directly on the metal deck ceiling. (e) Sections showing summer day roof pond insulation and night exposure. (f) Sections showing winter day roof pond exposure and night insulation. (g) Year-long record of the indoor temperature range compared to the outdoor range. (Drawings based in part on Sandia National Laboratory,* Passive Solar Buildings: A Compilation of Data and Results, *SAND 77-1204, 1977.)*



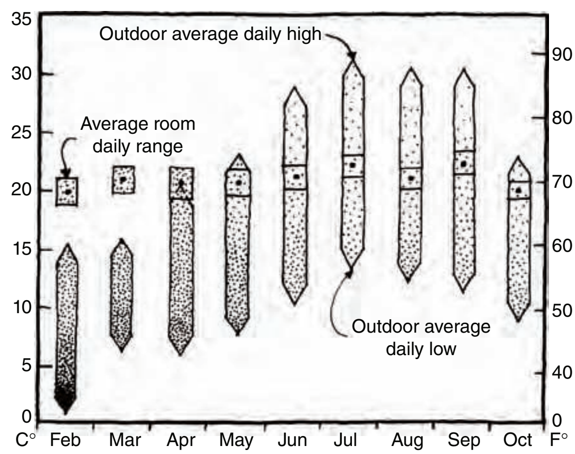
Roof pond cycle in summer

(*e*)



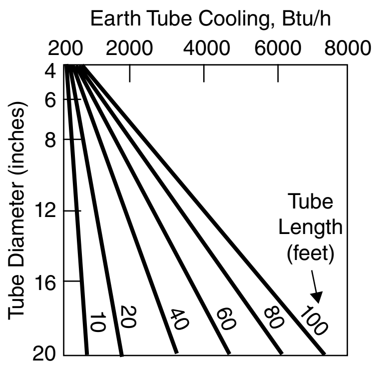
Roof pond cycle in winter

(*f*)



(*g*)

Fig. 10.14 *(Continued)*



Interactive Animation

Fig. 10.15 *Cooling of intake air provided by an earth tube in Btu/h. This tube is set in heavy, damp soil (k = 0.75 Btu/h °F ft [0.11 W/mK]) whose temperature around the tube is 65°F (18.3°C). The outdoor air entering the tube is at 85°F (29.4°C) and is moved at a flow velocity of 500 fpm (2.5 m/s). (Adapted by permission from Donald W. Abrams,* Low-Energy Cooling*; © 1986, Van Nostrand Reinhold Company.)*

who assumed a soil conductivity equal to that of heavy, damp earth. One of the most influential variables in earth tube performance is soil conductivity, so Fig. 10.16 (also from Abrams, 1986) compares the cooling performance of 6-in.-(150-mm)-diameter earth tubes when soil conductivity changes. Note that this design guideline (developed using I-P units) presents Btu/h cooling of *the outdoor air in the tube* rather than Btu/h ft^2 (for a typical ft^2 of building floor area). Therefore, two adjustments must be made: First, find the Btu/h cooling load of the outdoor air alone; second, adjust for the difference between hotter air outdoors and cooler air desired within the building.

See Section 10.8(g) for a more detailed calculation procedure for earth tubes in which tube depth, soil temperature, and soil conductivity are variable.

EXAMPLE 10.6 A partially underground nature center of 4000 ft^2 (372 m^2) in northern Pennsylvania, design DB = 87°F (65°C), has an hourly heat gain of 9.3 Btu/h ft^2 (29.3 W/m^2), of which 2.2 Btu/h ft^2 (6.9 W/m^2) are due to required outdoor air ventilation. If earth tubes are used only for cooling the fresh air, how many tubes at what length will be needed?

SOLUTION

First, the cooling needed from the earth tubes is (4000 ft^2)(2.2 Btu/h ft^2) = 8800 Btu/h (2580 W). Next, adjust this figure to account for actual project temperature conditions. If we accept 82°F (27.8°C) indoors (the walls are earth-sheltered and therefore provide some radiant cooling), then the total earth tube cooling needed is (8800 Btu/h)(87°F/82°F), or about 9330 Btu/h (2735 W).

From Fig. 10.15, assuming heavy, damp soil, a 60-ft- (18-m)-long tube 20 in. (500 mm) in diameter will deliver about 4500 Btu/h (1320 W); two such tubes will deliver about 9000 Btu/h (2640 W).

We return to this example in Section 10.8(g), Example 10.11. ■

See the more detailed calculation procedures that are given later in Section 10.8.

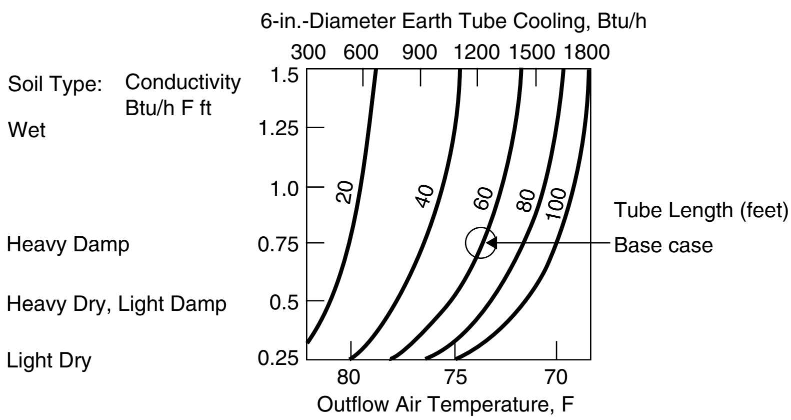


Fig. 10.16 *Six-inch-diameter (150 mm) earth tube cooling capacities as soil conductivity varies. The base case is a 6-in.-diameter (150 mm) earth tube 60 ft (18 m) long, shown in Fig. 10.15 to deliver 1200 Btu/h (352 W) of cooling at soil conductivity of 0.75 (0.11), with other conditions as specified in Fig. 10.15. (Adapted by permission from Donald W. Abrams,* Low-Energy Cooling*; © 1986, Van Nostrand Reinhold Company.)*

10.5 REINTEGRATING DAYLIGHTING, PASSIVE SOLAR HEATING, AND COOLING

This section offers guidance on a quick reconciliation of the preliminary investigations (to this point) and presents a "check" of envelope component U-factors and fenestration/floor area ratios as the design moves through various codes, standards, and design guidelines. Depending on the location, building type, and client's objectives, a very different mix of glass, insulation, and thermal mass could result from prescriptive conservation approaches compared to a passive solar heating focus or any of several approaches to passive cooling.

When prescriptive standards (such as those presented in Table H.1) appear to preclude either passive solar heating or passive cooling strategies in a building, the designer should remember that there are procedures for either window area trade-offs (in which more insulation in walls or roofs might allow more glass area) or methods to compare whole-building annual energy consumption that can demonstrate the superiority of using well-designed passive strategies over a simple conventional prescribed approach.

EXAMPLE 10.7 Consider a one-story residence in Billings, Montana. How does the fenestration area prescribed for code compliance compare with desirable fenestration areas for daylight, solar heating, and ventilation cooling?

SOLUTION

A residential energy code states that windows that are ≥15% of the floor area must have a maximum U-factor of 0.36 (SI: 2.0) and a maximum SC of 0.7. From Table E.15, windows #7 through #12 provide these values for U and SC (considered approximately equivalent to SHGC for this purpose).

We now need to assume the floor area and dimensions in order to proceed. A plan 32 ft (9.8 m) wide by 64 ft (19.5 m) long (with long walls facing north/south) yields a floor area of 2048 ft^2 (190 m^2). Most windows can be placed in the long walls for both daylight distribution and cross-ventilation. However, the south wall will need the most window area to facilitate solar heating. Tentatively, assign window areas as follows:

South window area	= 8% of floor area
North window area	= 5% of floor area
East and west window area	= 2% (1% each) of floor area
	15%

Daylight: For sidelighting, DF_{av} = 0.2 (window area/floor area), where all of the floor area is within 2.5 H of the window wall. If we assume that the ceiling height at the wall is 8 ft (2.4 m) with a window H = 7.5 ft (2.3 m), then the daylight area is 2.5 × 7.5 = 18.75 ft (5.7 m) deep. Light from opposite exterior walls produces the maximum daylight width of 2 × 18.75 = 37 ft (11.3 m). With our assumed maximum 32-ft (9.8 m) width, all floor area is within the daylight zone. For our total of 15% of floor area in fenestration, DF_{av} = 0.2 [0.15] = 0.03, or 3%. This seems to be sufficient according to the target DFs in Table 8.3.

TABLE 10.3 Cooling Load through Building Envelope (Example 10.8)

Net Area (m^2)	U-factor (W/m^2 K)	Δt (C°)	DETD (C°)	DCLF	Cooling Load (W)	Section	Reference	Net Area (ft^2)	DETD (F°)	U-factor (Btu/h ft^2 F°)	Δt (F°)	DCLF	Cooling Load (Btu/h)
371.6	0.51		24.4		**4620**	Roof	Table F.5	4000	0.09		44.0		**15,840**
37.6^a	1.36		9.1		**470**	South wall	Table F.5	405^a	0.24		16.3		**1,580**
71.1^a	2.7		9.1		**1750**	East wall	Table F.5	765^a	0.48		16.3		**5,990**
15.8^a	2.7		9.1		**390**	North wall exposed	Table F.5	170^a	0.48		16.3		**1,330**
98.9^a	1.41	11.2^b			**1560**	Party walls		1065^a	0.25	20^b			**5,330**
3.25	1.08		13.1		**50**	Doors: S	Table F.5	35	0.19		23.6		**160**
3.25	1.08	11.2^b			**40**	N	Table F.5	35	0.19	20^b			**130**
3.25	1.08		13.1		**50**	E	Table F.5	35	0.19		23.6		**160**
5.6	(4.6)^c			97.9	**550**	Windows: S	Table F.6	60	(0.81)^c			31	**1,860**
2.8	(4.6)^c			72.6	**200**	N	Table F.6	30	(0.81)^c			23	**690**
				Total:	**9680**							Total:	**33,070**

[a]Calculated from gross wall area less windows and door areas.

[b]Design temperature difference, inside to outside.

[c]DCLF for glass includes the U-factor.

Passive Solar Heating: Windows #7 through #12 (Table E.15) are under consideration. From Table G.1, footnote c, windows #7 and #12 qualify as superior-performance glazings. For Billings, Montana, a south glass/floor area "low" ratio of 0.16 would produce SSF = 53%. From Table G.2, such an SSF would require at least 3.8 surface area units of interior masonry surface for each unit area of south glass. However, only 8% south window area/floor area is allocated. The designer can:

- Reallocate window area so that essentially all windows face south (with daylight and cross-ventilation penalties)
- Increase the total window area to more than 15%, with correspondingly better fenestration U-factors required (from applicable energy code, up to 21% of floor area would require U = 0.29 [SI: 1.65])
- Settle for a lower SSF with only 8% south window area/floor area

Cross-Ventilation: First, we need a quick estimate of heat gains. From Table G.3:

A. Internal gains from people and equipment: Assume 4 people at 230 Btu/h (67 W) plus 1200 Btu/h (352 W) from appliances:

$$(4 \times 230) + 1200 = 2120 \text{ Btu/h } (621 \text{ W})$$

$$2120 \text{ Btu/h}/2048 \text{ ft}^2 = 1.04 \text{ Btu/h ft}^2 \ (3.3 \text{ W/m}^2)$$

B. Lighting: Assume with 3% DF a gain of about 2.0 Btu/h ft^2 (6.3 W/m^2).

C. Gain through envelope: Billings's design temperature (Table B.1) is 87.2°F (30.7°C).

Externally shaded window gains = (0.15) × 16 = 2.4 Btu/h ft^2 (7.6 W/m^2); gain through walls: total vertical area = [(2 × 32 ft) + (2 × 64 ft)] = 1536 ft^2 (143 m^2). Of this, window area = (0.15 × 2048) = 307 ft^2 (28.5 m^2); opaque wall area = 1536 – 307 = 1229 ft^2 (114 m^2).

To meet the energy code, frame walls must have a U-factor no greater than 0.073 (SI: 0.4), whereas masonry walls may have a maximum U-factor of 0.08 (SI: 0.45). Therefore,

Gain through walls = wall to floor area (1229 ft^2 wall area / 2048 ft^2 floor area = 0.6) × 0.08 × 15 = 0.72 Btu/h ft^2 (2.3 W/m^2).

Gain through roof: Assume roof area equal to floor area, and to comply with the energy code, a maximum U-factor of 0.033 (SI: 0.19). Therefore,

$$\text{gain through roof} = (1.0) \times 0.033 \times 35 = 1.16 \text{ Btu/h ft}^2 \ (3.7 \text{ W/m}^2).$$

D. For an open building (using cross-ventilation)

$$\text{total heat gain} = 1.04 + 2.0 + 2.4 + 0.72 + 1.16 = 7.32 \text{ Btu/h ft}^2 \ (23.1 \text{ W/m}^2).$$

We can assume a total operable area of perhaps 90% of the glazed area using fully openable casement windows. With 8% floor area in south windows and 5% in north windows, the maximum available ventilation area = 0.9 × 5% = 4.5% of the floor area. From Fig. 10.5, it appears that this rate of heat gain can be removed through this inlet area by a wind velocity of only about 2 mph (3.2 km/h).

Summary: Probably increase the south glass area (and the overall ratio of window/floor area) and use windows with lower U-factors, with summer external shading. The floor and many interior wall surfaces will be faced with thermally massive materials. ■

10.6 APPROXIMATE METHOD FOR CALCULATING HEAT GAIN (COOLING LOAD)

Unlike the calculations for winter worst-hour heat loss, which simply assume nighttime conditions and few if any internal gains, summer worst-hour heat gain calculations are very complex. During the summer worst-hour heat gain is assumed to occur during the daytime under active occupancy conditions, so solar gains and internal gains from lights, people, and equipment *must* be included. Summer calculations are complicated further by the fact that the hourly change in summer load can be very great, both from changing sun position and from changing internal loads. Also, in summer the thermal mass of the building becomes influential, delaying the impact of the radiant component of heat gains from all sources.

Before making any detailed calculations for passive cooling performance, consider a simplified heat gain procedure that has been developed for residential buildings; with some risk and some judgment, it can also be used for a quick *approximation* of the conditions in commercial buildings. This simplified method was devised to be used with buildings that, like residences:

1. Are occupied and air-conditioned (internal temperatures closely controlled) for 24 hours per day. (Separate calculations can be done for weekdays and weekends.)
2. Derive much of their gains through the building envelope and ventilation rather than internally.
3. Can accept the effects of undersized cooling equipment, with the result that unusually hot weather means noticeably higher indoor temperatures (and that interior temperatures will vary during a typical summer day).

Because many commercial buildings do *not* have these characteristics, this method should not be applied if very accurate estimates are desired for such buildings. However, the method is rapid, if risky, and though different methods are offered by ASHRAE, we include this method as an easy way to gain understanding of the necessary inputs to more complex calculations and software programs.

(a) Gains through Roof and Walls

The sensible heat gains through opaque parts of a building's envelope are calculated with the equation:

$$q = U \times A \times \text{DETD}$$

where

U-factors are for summer

A = area of the roof or wall

DETD (design equivalent temperature differences) values are listed for broad categories of construction in Table G.5

The DETD values are based on an average indoor temperature of 75°F (23.8°C), and the outdoor conditions listed. Note that for lightweight wall construction (and doors) the DETD varies by orientation. A means of correcting DETD for other temperatures is as follows.

Where the design temperature difference (outdoor design temperature minus assumed indoor temperature of 75°F [23.8°C]) is not an even increment of 5F° (2.8C°), the equivalent temperature difference should be corrected 1F° (0.5C°) for each 1F° (0.5C°) difference from the tabulated values.

For rapid approximation, however, select the DETD directly from the table for the conditions nearest to your building/climate combination. The design temperature for your climate is listed in Appendix B.

Note that Table G.5 lists considerably higher DETD values for roofs than for any other component. This is due to the *sol-air temperature*, the effective temperature of outdoor air just above a solar-heated surface. When the sun strikes the surface, it adds its heat to that from the outdoor air. The darker the surface, the greater the resulting effective (sol-air) temperature. This elevated outdoor temperature thus increases the Δt through the roof, resulting in greater heat gains. The sol-air formula was discussed in Chapter 7. Sol-air temperature is discussed in the 2013 *ASHRAE Handbook—Fundamentals*, Chapter 18. Uninsulated or poorly insulated roofs of darker colors are particularly impacted by sol-air temperature.

(b) Gains through Glass

The quick way to approximate these gains is

$$q = A \times \text{DCLF}$$

DCLF (design cooling load factor) values are listed in Table G.6 and *include the U-factors* as well as the equivalent temperature differences. (These DCLF values do *not* correspond to the worst-hour gains; they were obtained by averaging the hours from 5:30 A.M. to 6:30 P.M. at both 30°N and 40°N latitudes.) Again, the DCLF values were based on an inside temperature of 75°F (23.8°C) and outside temperatures as listed in Table G.6. (For *rapid* approximation, ignore the corrections procedure shown in note *a*.) Glass protected by exterior shading devices that exclude all direct sun may be considered equal to the values listed in Table G.6 for "north glass protected by awnings."

(c) Gains from Outdoor Air

In residences, outdoor air often enters by infiltration. In many other buildings, codes require the deliberate introduction of outdoor air by mechanical ventilation. Whichever way outdoor air enters your building in summer, the sensible heat gain can be calculated by either

$$q_{\text{infiltration}} = (A_{\text{exposed}})\,(\text{infiltration factor})$$

where A_{exposed} is the total area of exposed wall surface, including windows and doors, and the infiltration factor is found from Table G.7, or

$$q_{\text{mechanical ventilation}} = (Q)\,(\text{ventilation factor})$$

where Q is the volume of outdoor air (cfm or L/s; see Chapter 5), and the ventilation factor is found from Table G.7. Latent loads will be addressed later.

(d) Gains from People

Only the sensible gains are tabulated, because a simple overall factor for latent gains is included later. The rate of heat gain from people in various activities is shown in Table G.8; values in the "Sensible Heat" column are generally used. (For residences, sensible heat gain per occupant is often assumed at 230 Btu/h [67 W]):

$$q_{\text{people}} = (\text{number of occupants}) \times (\text{sensible gain per occupant})$$

(e) Gains from Lighting

The power supplied to electric lamps (those that normally are on while cooling equipment is functioning) can be added directly to the sensible heat gain. Be sure to include ballast heat gains along with fluorescent lamps, usually done by taking *from 1.12 to 1.2 times the total bulb wattage* of such lamps (use the lower figure with energy-efficient ballasts).

(f) Gains from Equipment

In residences, a standard assumption is that 1200 to 1600 Btu/h (350 to 470 W) of sensible heat gain is produced by appliances. (Other residential heat loads are assumed to be vented.) For other buildings, see the gains of specific pieces of equipment given in Tables G.9 and G.10.

(g) Latent Heat Gains

Latent heat gains vary a great deal with the type of occupancy, but this simple method assumes that the latent gains are closely associated with outdoor air infiltration. Figure 10.17 is a method to estimate *additional latent heat* as a percentage of *total sensible gains*. The design DB and mean coincident WB temperatures from Appendix B, as well as the relative tightness of building construction, determine the latent percentage of total sensible gain. A minimum of 10% and a probable maximum of 30% additional latent are recommended limits.

EXAMPLE 10.8 A one-story office building (Fig. 10.18) is located in the eastern United States near 40°N latitude. The adjoining buildings on the north and west are not conditioned, and their inside air temperatures are, for simplicity, assumed equal to the outdoor air temperature at any time of day. This is an unusual building both for its uninsulated walls and for very high lighting loads. What are the heat gains, hence the cooling load?

Roof construction: 4.5-in. (115-mm) flat roof deck of 2-in. (50-mm) gypsum slab on metal roof deck, 2-in. (50-mm) rigid above-deck roof insulation, surfaced with two layers of mopped felt vapor-seal built-up roofing having dark-colored gravel surface, no false ceiling. Summer U = 0.09 Btu/h ft^2 °F (0.51 W/m^2 °C).

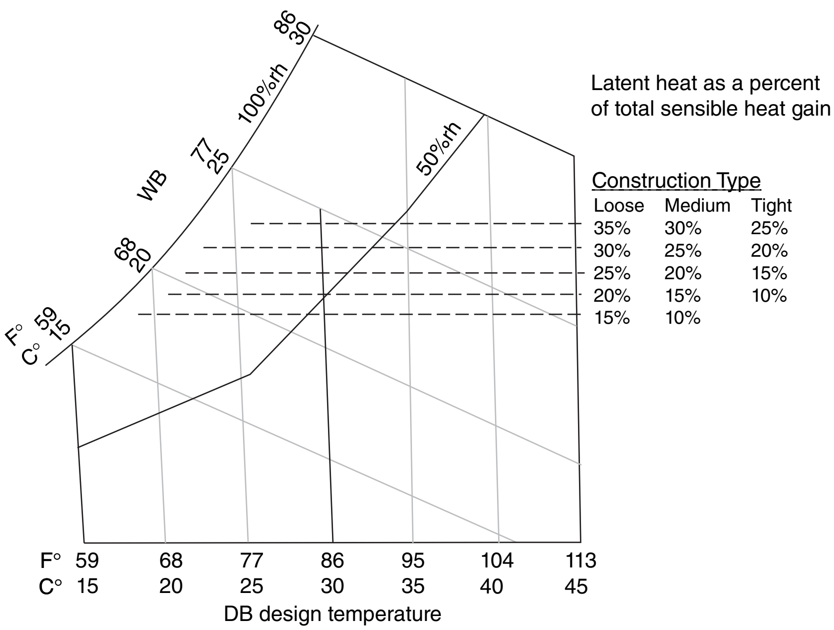


Fig. 10.17 *Estimating latent heat gain as a percentage of total sensible heat gain, assuming that these additional latent gains are closely associated with outdoor air infiltration. Relative tightness of building construction is included as a variable. Design DB and mean coincident WB temperatures may be found in Appendix B.*

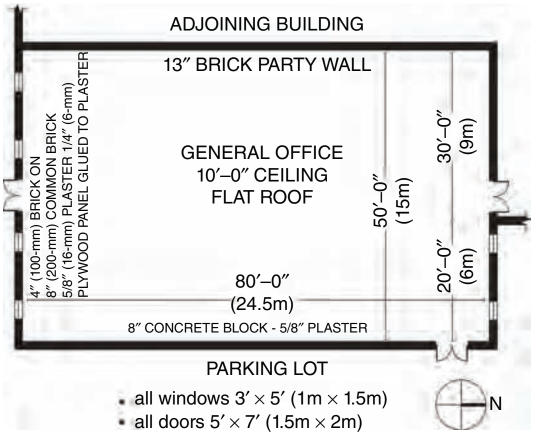


Fig. 10.18 *Plan of the office building for which heat gain calculations are shown in Example 10.8 (and in Table 10.3). (Drawn by Tyler Mavichien.)*

South wall construction: 4-in. (100-mm) face brick, 8-in. (200-mm) common brick, 0.625-in. (16-mm) plaster, 0.25-in. (6-mm) plywood panel glued on plaster. Summer U = 0.24 Btu/h ft^2 °F (1.36 W/m^2 °C).

West wall and adjoining north party wall construction: 13-in. (325-mm) solid brick, no plaster. Interior partition U = 0.25 Btu/h ft^2 °F (1.40 W/m^2 °C).

North exposed wall and east wall construction: 8-in. (200-mm) concrete block and 0.625-in. (16-mm) plaster. Summer U = 0.48 Btu/h ft^2 °F (2.73 W/m^2 °C).

Floor construction: 4-in. (100-mm) concrete slab-on-grade

Fenestration: 3-ft × 5-ft (1-m × 1.5-m) nonoperable windows of regular plate glass with light-colored venetian blinds. Summer U = 0.81 Btu/h ft^2 °F (4.6 W/m^2 °C).

Front doors: Two, 2.5 × 7 ft (1.5 m × 2 m)

Side doors: Two, 2.5 × 7 ft (1.5 m × 2 m)

Rear doors: Two, 2.5 × 7 ft (1.5 m × 2 m), interior

Door construction: Light-colored 1.75-in. (45-mm) steel door with solid urethane core and thermal break. Summer U = 0.18 Btu/h ft^2 °F (1.08 W/m^2 °C).

(U-factors for all doors and outside walls were calculated assuming a wind speed of 7.5 mph [12 km/h]. For party and inside walls, still air was assumed.)

Outdoor design conditions: Dry-bulb temperature, 94°F (35°C); daily range, 20F° (11C°). Wet-bulb temperature, 77°F (25°C).

Indoor design conditions: Dry-bulb temperature, 75°F (24°C); wet-bulb temperature, 62.5°F (18°C)

Occupancy: 85 office workers from 8:00 A.M. to 5:00 P.M.

Lighting: 17,500 W fluorescent, from 8:00 A.M. to 5:00 P.M.; and 4000 W tungsten, continuous

Equipment: This example does not include any office equipment.

Ventilation: The ventilation rate is 15 cfm (7 L/s) per person, for a total of 1275 cfm (595 L/s).

The conditioning equipment is located in the adjoining building to the north.

Determine the sensible, latent, and total space cooling load at design conditions.

SOLUTION

Before beginning the calculations, *estimate* the heat gain using the design guideline procedure of Table G.3.

People (omitting equipment in this example):

$$2.3 \times 2^{a} = 4.6 \text{ Btu/h ft}^2 \ (14.5 \text{ W/m}^2)$$

Lighting^b:

$$21{,}500 \text{ W}/4000 \text{ ft}^2 = 5.4 \text{ W/ft}^2 \times 3.41 \text{ Btu/h W} = 18.4 \text{ Btu/h ft}^2 \ (58 \text{ W/m}^2)$$

Envelope gains:

Windows:	90 ft^2/4000 ft^2 × 18^c = 0.4
Walls:	
South:	405 ft^2/4000 ft^2 × 0.24 × 19^c = 0.5
East, north exposed:	935 ft^2/4000 ft^2 × 0.48 × 19^c = 2.1
Party:	1065 ft^2/4000 ft^2 × 0.25 × 19^c = 1.3
Roof:	4000 ft^2/4000 ft^2 × 0.09 × 39^c = 3.5
Ventilation:	1275 cfm/4000 ft^2 × 21^c = 6.7

Total 37.5 Btu/h ft^2 (118 W/m^2)

---

[a] 4000 ft^2/85 people = 47 ft^2 per person, more than double the heat gain at a lower density of 100 ft^2 per person that is assumed in this approximate procedure, so increase people gain by a factor of 2.

[b] This is considerably in excess of the lighting loads upon which this approximate procedure is based. Without a detailed knowledge of the actual installed lighting loads, the design guideline would have suggested a lower load as follows.

$$\text{DF} = 0.2 \times \frac{90 \text{ ft}^2 \text{ windows}}{4000 \text{ ft}^2 \text{ floor}} = 0.5\% \text{ DF}$$

which is <1, therefore suggesting a load of only 5.1 Btu/h ft^2 (16.1 W/m^2)

[c] Interpolate for 95°F (35°C), between 90°F (32.2°C) and 100°F (37.8°C) outdoor temperature.

Cooling load due to heat gain through building envelope: The heat gains through roof, exposed walls, and doors shown in Table 10.3 were calculated by

$$q = U \times A \times \text{DETD}$$

for which DETD values are taken from Table G.5. In line with the approximate (and therefore rapid) nature of this calculation method, *no corrections* were made to DETD values to adjust for either outside or inside design temperatures differing from those listed, and actual gains were rounded to the nearest 10. The climate's daily temperature range is medium; the roof is dark (typical of commercial buildings in air-polluted areas). An outside design temperature of 95°F (35°C) was used. To keep things simple, the temperature difference through party walls was made equal to that on which the table was based; in this case, 95 − 75 = 20F° (35 − 23.8 = 11.2C°).

Cooling load due to heat gain through glass: These heat gains were calculated by

$$q = A \times \text{DCLF}$$

for which the DCLF values (which include the U-factor) were taken from Table G.6. Again, no corrections were made, and gains were rounded to the nearest 10.

Cooling load due to heat gain from lighting, people, and equipment: The rate of heat gain from the lighting can be approximated simply by taking the energy input (including that required for fluorescents ballasts). For fluorescent lamps, 17,500 W × 1.2 ballast factor

$$= 21{,}000 \text{ W } (71{,}650 \text{ Btu/h}).$$

For incandescent lamps,

$$4000 \text{ W } (13{,}650 \text{ Btu/h})$$

The sensible gains from people can be determined from Table G.8. For office work, assume 75 W (250 Btu/h):

$$85 \text{ people} \times 75 = 6380 \text{ W } (21{,}250 \text{ Btu/h})$$

Heat gains from office equipment are ignored in this example. (See Tables G.3 and G.9 for typical ranges of such gains.) The sensible gains from lighting, people, and equipment thus total 106,550 Btu/h (31,380 W).

Cooling load due to ventilation or infiltration: Because this is a commercial building incorporating deliberate introduction of outdoor air, infiltration will be ignored. This example assumes ventilation at 15 cfm (7 L/s) per person. Total mechanical ventilation is 1275 cfm (595 L/s). Sensible heat gains (from Table G.7):

Mechanical ventilation:

$$22.0 \times 1275 \text{ cfm} = 28{,}050 \text{ Btu/h}$$
$$(13.6 \times 595 \text{ L/s} = 8090 \text{ W})$$

Latent heat gains: The climate description suggests a typical northeastern U.S. climate at 40°N latitude. Newark, New Jersey (91°F DB, 73°F WB [32.8°C, 22.8°C]), and Philadelphia, Pennsylvania (90 DB, 74 WB [32.2°C, 22.3°C]), are examples. From Fig. 10.17, estimate latent gain as about 20% of the total sensible load.

	W	Btu/h
Sensible gains, envelope	9680	33,070
Sensible gains, lights and people	31,380	106,550
Sensible gains, ventilation	8090	28,050
Sensible gains, total	49,150	167,670
Latent gains (20%, this example)	9830	33,530
Total latent and sensible heat gains	58,980	201,200

■

10.7 DETAILED HOURLY HEAT GAIN (COOLING LOAD) CALCULATIONS

Ordinarily, the approximate method of calculating the peak cooling load (discussed in Section 10.6) is sufficient for a designer's preliminary estimates of cooling equipment size for a small building. However, much more detailed procedures are used by engineers to actually size equipment and to assess the peak-load impact of various design options such as shading devices.

Three detailed methods for calculating heat gains and equipment cooling loads are described in the 1997 *ASHRAE Handbook—Fundamentals* (Chapter 28): (1) The transfer function method (TFM), (2) the total equivalent temperature differential, time-averaging method (TETD/TA), and (3) a one-step method, cooling load temperature difference/cooling load factor (CLTD/CLF). Both TFM and TETD/TA yield hourly values over a 24-hour day. They account for thermal storage by building mass, which can significantly shift the impact of instantaneous heat gains on the actual cooling load for the HVAC equipment, as shown in Fig. 10.19. CLTD/CLF yields a 1-hour value that also accounts for the effects of thermal mass.

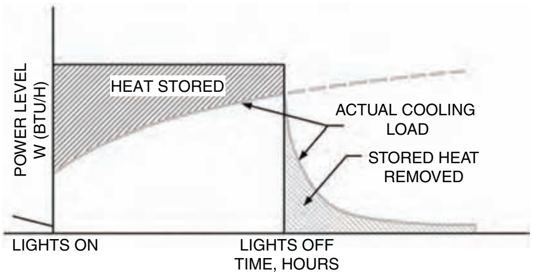


Fig. 10.19 *Thermal storage effect in the cooling load caused by electric lighting. (Reprinted with permission of ASHRAE, from the 1997* ASHRAE Handbook—Fundamentals. *This citation to an older version of the* Handbook *is intentional and provides access to historic reference information of ongoing interest.)*

Though these methods are rarely used by architects, a summary of the results of the calculations by each method for the office building of Example 10.8 is shown in Table 10.4.

The quick and uncomplicated heat gain methods shown in Table G.3 and Section 10.6 served the simple building in Example 10.8 rather well. Had the design guideline (Table G.3) been used to size a cooling system, it would have matched the TFM worst-hour sensible gains, but it was only about 84% of the other methods' worst-hour sensible gains. Latent gain estimates would have been necessary as well. The approximate method underpredicted latent gains, but the total (latent and sensible) gains of this quick, by-hand method ranged from 83% to 95% of the computer-based methods' results.

As a quick approximation for estimating the overall equipment size or passive cooling approach, these by-hand methods are adequate for smaller and simpler buildings. When utilizing these quicker methods, keep in mind that some design judgment may require subdividing the calculations or even changing some of the multipliers to reflect unusual conditions. A designer's checklist of considerations for heat gain should include:

1. Characteristics of the building envelope: materials, sizes, external surface colors, and shapes
2. Building location and orientation, as well as the extent of external shading of the building by trees or adjacent structures
3. Outdoor design conditions
4. Indoor design conditions: DB, WB, and ventilation rate
5. The schedule of lighting, occupancy, equipment, and any other processes that contribute to internal heat gain
6. Thermal zoning requirements

10.8 DETAILED CALCULATIONS: PASSIVE COOLING PERFORMANCE

When outdoor air is 85°F (30°C) or below, it is marginally possible to cool buildings by simple ventilation, maintaining conditions indoors that are within the adaptive thermal comfort zone. The procedures in this section go beyond the quicker design

TABLE 10.4 Comparison of Methods of Heat Gain Calculation (Example 10.8)

	Maximum Hourly Gain (W)			*24-h Average Gain (W/m^2)*			*Maximum Hourly Gain (Btu/h)*			*24-h Average Gain (Btu/h ft^2)*		
Method	**Sensible**	**Latent**	**Total**	**Sensible**	**Latent**	**Total**	**Sensible**	**Latent**	**Total**	**Sensible**	**Latent**	**Total**
Design guideline (Table G.3)	(118/m^2)						(37.5/ft^2)					
Approximate[a] (Section 10.6)	49,150 (131/m^2)	9830	58,980				167,670 (41.9/ft^2)	33,530	201,200			
Transfer Function[b] (worst hour 4:00 P.M.)	41,415 (110/m^2)	15,040	56,455	68.3	32.0	100.3	149,623 (37.4/ft^2)	61,168	210,791	21.3	12.5	33.8
CLTD/CLF[b] (for 4:00 P.M. only)	53,499 (143/m^2)	15,040	68,489				179,140 (44.8/ft^2)	63,208	242,348			
TETD/TA[b] (worst hour 4:00 P.M.)	50,096 (134/m^2)	15,040	65,136	68.3	32.0	100.3	169,082 (42.3/ft^2)	61,168	230,250	21.3	12.5	33.8

[a]See Table 10.3 and Example 10.8 for calculations.

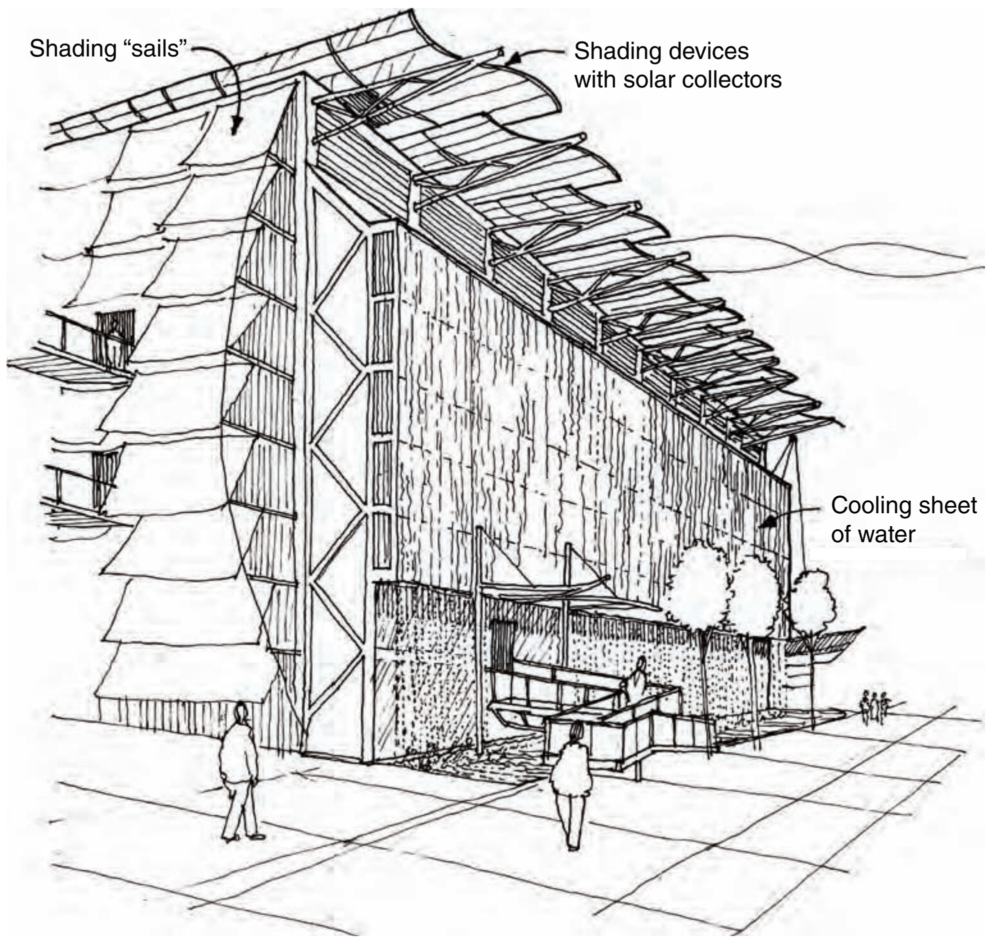
[b]Previously extracted, with permission of ASHRAE, from 1997 *ASHRAE Handbook—Fundamentals*, Chapter 28. This table is maintained for the purpose of this example; recently ASHRAE has developed a more complex calculation.

guidelines that appeared in Section 10.4 and allow the designer to better adjust a preliminary design to the program and the climate.

In the many climates in which the outdoor temperature is above 85°F (30°C) for a large number of working-day hours, buildings that are closed to the hot exterior during those hours are practical. Between 80° and 85°F (27° to 30°C), outdoor air can keep people within the comfort zone if it moves across the body fast enough. In areas with reliable winds, open buildings are feasible up to 85°F (30°C). Between 55° and 69°F (13° and 21°C), outdoor air is cool enough to use in place of, or to greatly supplement, mechanically cooled air if the humidity is sufficiently low. Passive cooling is even easier under these conditions.

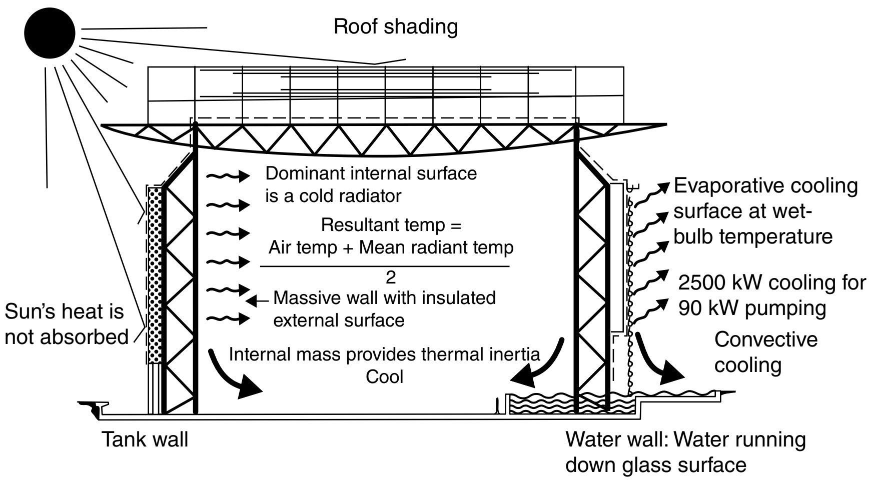
To introduce these more detailed methods, consider the United Kingdom Pavilion (now dismantled) at the 1992 Seville World Expo (Fig. 10.20). This was an unusually large passive building (213 ft × 105 ft × 82 ft high [65 m × 32 m × 25 m high]), with an unusually wide collection of passive cooling techniques, inspired by the traditional cooling methods of hot, dry southern Spain: shading, water, and mass. The Expo was an April to October event, with the greatest comfort challenge in July–August, when average daily temperatures range from about 64° to 102°F (18° to 39°C).

Shading began with the flat roof, where standing wave-form racks carried both translucent fabric

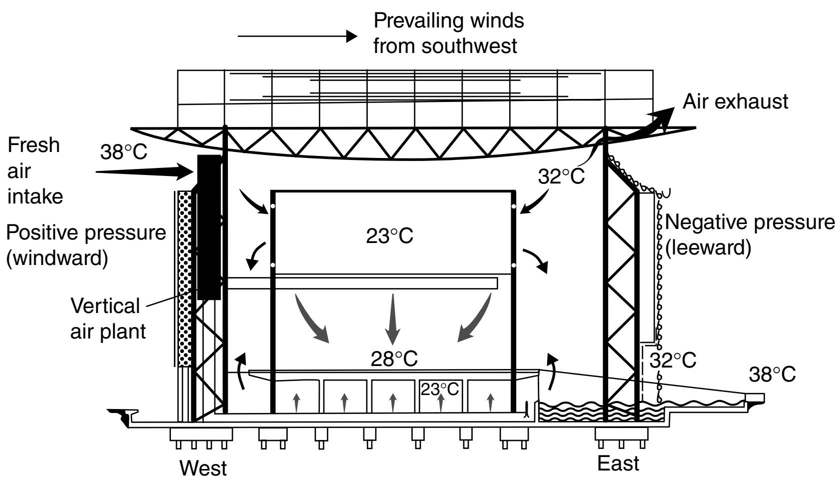


(*a*)

Fig. 10.20 *The United Kingdom Pavilion at the Seville (Spain) World Expo, 1992. (a) Waveform shading devices on the roof also carry PV cells, whose electricity helps pump water from the pool that flows continuously over the east glass wall. (b) Section (east–west) with a combination of cooling strategies. (c) Section (east–west) with estimated maximum temperatures. (Sections are courtesy of Ove Arup Partnership, London.)*



(*b*)



(*c*)

Fig. 10.20 *(Continued)*

shades and PV cells facing south. Outside the south façade, projecting sail-like "fly-sheets" kept off direct sun. The east and west façades used different strategies.

Water became a theme of the exhibit, beginning with the wavelike silhouette on the roof and featured as a continuous sheet of water streaming down the east façade, dripping into a pool. The water was pumped, with some power (about 50%) provided by the PV cells on the roof racks. Waiting visitors standing in line outside were treated to the sight and sound of this controlled waterfall, then crossed a bridge over the pond, flanked by spray fountains, to enter the Pavilion. The pond continued below the east wall, exposed to the interior. Water also played a much less evident role on the west facade.

Mass was a particular challenge, because the building was designed as a lightweight structure to be dismantled and largely reused elsewhere. The west wall consisted of white metal containers filled with water to reflect the greater part of the direct sun and store the remainder during the day, radiating by night to cooler outdoor air.

Thermal zoning was a vital part of this concept, recognizing that people were entering from very hot, unshaded conditions and that most visitors would then move through rather quickly.

Passive cooling was given the task of keeping visitors cooler than the outside; mechanical refrigeration was responsible for maintaining even lower temperatures only where people gathered over extended periods of time, as in the "pods" that contained the restaurant and the cafeteria. Gardner and Hadden (1992) describe how the typical July visitor left a sunny outdoor environment at about 100°F (38°C) for the cooler interior at about 90°F (32°C) supplemented by radiant coolth from the huge east glass wall at a maximum of 75°F (24°C) thanks to evaporation from the running water. Exhaust air from the pods lowered temperatures in their vicinity to about 82°F (28°C). The pods themselves, maintained at about 73°F (23°C), were entered only after the visitor underwent a lengthy transition through the Pavilion from the hot outdoors.

To some extent, both cross- and stack ventilation were also involved, despite the outdoor heat; the hottest air indoors rose to the ceiling and was replaced by outdoor air that was cooled slightly as it passed through the watery gap between the east glass wall and the pond. Very high vents at the top of both east and west walls admitted wind to sweep across the ceiling and remove the hottest air.

(a) Cross-Ventilation

Once again, remember that cross-ventilation cooling works only when the *outside is cooler than the inside*. Otherwise, why bring in air that is warmer to try to cool a space? For ventilation using windows, the quantity of outdoor air admitted is termed *V*. The flow of air from inlet windows through the building to outlet windows should have a minimum of obstacles. In I-P units,

$$V = C_\upsilon A \upsilon$$

where
V = volume flow rate of air, cfm
A = area of operable windows on inlet side or sides, ft^2
C_υ = effectiveness factor (dimensionless) that adjusts for different wind orientations: 0.5 to 0.6 for winds perpendicular to the window openings; 0.25 to 0.35 for wind diagonal to the window openings
υ = velocity of wind, fpm (= mph × 88)

In SI units,

$$V = 1000 C_\upsilon A \upsilon$$

where
V is in L/s (= m^3/s multiplied by 1000)
A is in m^2
υ is in m/s

The sensible heat removed by this flow of outdoor air through indoor spaces was presented in Chapter 7:

$$q_\upsilon = (V)\,(1.1)\,(\Delta t)$$

where
q_υ = sensible heat exchange due to ventilation (Btu/h)
V = volume flow rate, in cfm of outdoor air introduced
Δt = temperature difference between outdoors and indoors (F°)
1.1 = a constant (the density of air multiplied by the specific heat of air); units are Btu min/ft^3 h °F

In SI units, this becomes

$$q_\upsilon = (V)\,(1.2)\,(\Delta t)$$

where q_υ is in watts, V is in L/sec, 1.2 is a constant (the density of air [1.20 kg/m^3] multiplied by the specific heat of air [1.0 kJ/kg K]), and Δt is in K.

A further modification to these cooling formulas is usually necessary because wind data are typically taken at airports at a height of about 30 ft (10 m) above open, unobstructed ground. Rarely will buildings that rely on cross-ventilation be so favorably situated. Figure 10.21 shows correction factors to be applied to such airport wind velocities for variations in terrain and height above the ground. The dimensionless correction factor should then be applied to the quantity *V*, usually resulting in a reduced volume flow rate.

A more detailed procedure for calculating cross-ventilation in residences given in Chandra et al. (1986) accounts for such factors as neighboring buildings and terrain, height of opening above grade, insect screens, and framing members within openings. To analyze natural ventilation in even more detail, wind tunnel tests or computation fluid dynamic (CFD) analyses are more likely to be useful than are detailed hand calculations.

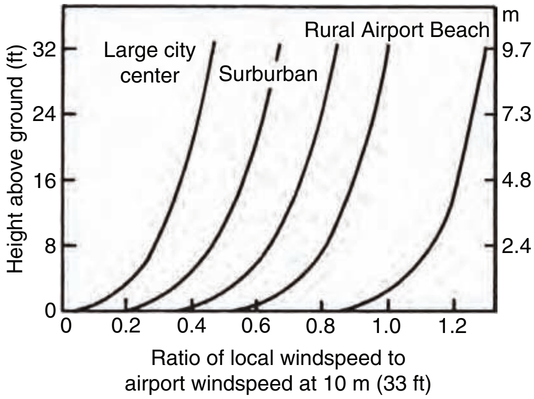


Fig. 10.21 *Wind speed variation with height for various terrains. (From* Cooling with Natural Ventilation*, Florida Solar Energy Center, published by the Solar Energy Research Institute.)*

(b) Stack Ventilation

This is another reminder that stack ventilation cooling works only when the *outside is cooler than the inside*. The stack effect needs several conditions: warmer air indoors that can enter the bottom of the stack, cooler air outdoors, and low inlets to admit that cooler outdoor air to the building. This cooler outdoor air picks up heat from the building and enters the bottom of the stack. Within the stack, this now-warm air rises, because it is less dense—therefore lighter—than the cooler outdoor air that surrounds the top of the stack.

The following equation applies when there is no significant resistance to airflow within the building. To calculate ventilation cooling by the stack effect:

$$V = 60\,KA\sqrt{2gh(t_i - t_o)/t_i}$$

where
V = airflow rate, cfm
K = discharge coefficient for opening; assumed to equal 0.65 for multiple inlet openings
A = in square feet, the smaller of either total free area of inlet or outlet openings or horizontal cross-sectional area (throat area) of the stack
g = gravitational constant, 32.2 ft/s^2
h = height of the stack from inlet to outlet, ft
t_i = temperature indoors ($>t_o$), °R
t_o = temperature outdoors ($< t_i$), °R
Note: °R = °F + 459.67.

In SI units,

$$V = KA\sqrt{gh(t_i - t_o)/t_i}$$

where
V = airflow rate, m^3/s (× 1000 = L/s)
K = discharge coefficient for opening, assumed to equal 0.65 for multiple inlet openings
A = in m^2, the smaller of total free area of inlet or outlet openings or horizontal cross-sectional area (throat area) of the stack
g = gravitational constant, 9.81 m/s^2
h = height of stack from inlet to outlet, m
t_i = temperature indoors ($>t_o$), K
t_o = temperature outdoors ($< t_i$), K
Note: K = °C + 273.15.

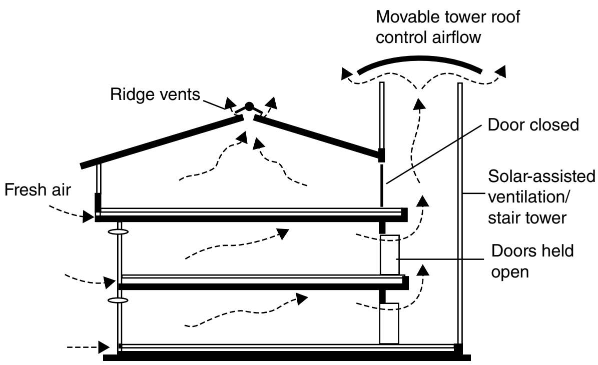
The height of a stack and its cross-sectional area present an unusual opportunity for building form. The Inland Revenue Centre at Nottingham, England (Fig. 10.22), took advantage of this opportunity to provide cylindrical stair towers at corners (or at ends) of its buildings as stack ventilators. These are three- and four-story buildings, with a width of 44.6 ft (13.6 m) to encourage both daylight penetration and natural ventilation. The tower stacks serve all floors except the top. The fabric-covered top of each tower is 23 ft (7 m) above the highest floor served, and can be raised up to 3.3 ft (1 m) or lowered (closed) to vary the flow of exhaust air. The stacks are enclosed in glass block so that solar gain can assist the heating—and thus the flow—of air by day within the stack. Berry et al. (1995) report that the airflow increased from 4.8 to 6.2 ACH with the tower operating in solar mode.

Each lower floor has a 43-ft^2 (4-m^2) opening to each stack, with the (openings) doors held open magnetically unless fire alarms close them. This rather small opening to the stack (relative to the floor area served) is the limiting factor in the outward flow of heated air; to supplement the supply of outdoor air, small three-speed fans are installed in the floor below each window to draw in fresh air, then distribute it through a wide floor grille. The triple-glazed windows are also operable, both as sliding "doors" and as tilt-ins from the top.

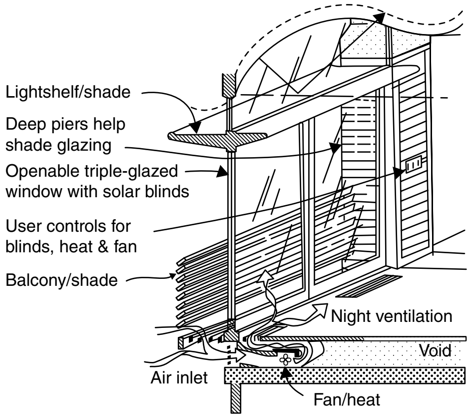
This fan-assisted stack effect is used on summer nights to help precool the building for the following day; the lower floors feature very large areas of exposed structural mass in their precast concrete ceilings.

(*a*)

(*b*)



(*c*)



(*d*)

Fig. 10.22 *The Inland Revenue Centre at Nottingham, England. (a) Cylindrical stair towers at the corners and ends of three- and four-story office blocks act as stacks; solar gain through glass helps increase the flow of exhaust air. (b) Tops of the towers are fabric and can be raised to increase the stack aperture and therefore increase the flow. (Photos courtesy of Vaughan Reynolds.) (c) Section of a three-story wing with a stack ventilation stair tower. (Drawing courtesy of Ove Arup Partnership, London.) (d) Section perspective with fan-assisted intakes below each window and an exposed precast concrete ceiling that helps store heat for night ventilation cooling.*

The top floor is a lighter-weight structure, with the stack effect culminating in a ridge vent. Monitoring reveals that this floor is usually a few degrees warmer than the massive night-ventilated lower floors.

(c) Night Ventilation of Thermal Mass

Before doing these detailed calculations, be sure that (1) you have checked your summer climate against the passive cooling design strategies (Fig. 10.2) and that night ventilation of thermal mass is appropriate, and (2) your building and climate have been checked for approximate performance based on the design guidelines (Fig. 10.8) for this cooling strategy. Also have in mind a positive night ventilation strategy; Fig. 10.23 shows an example of a forced-air system integral with a concrete joist-and-girder structural system. The following procedure is adapted from one developed by Karen Crowther for a workshop at the Fifth National Passive Solar Conference in Amherst, Massachusetts, as presented in Miller (1980).

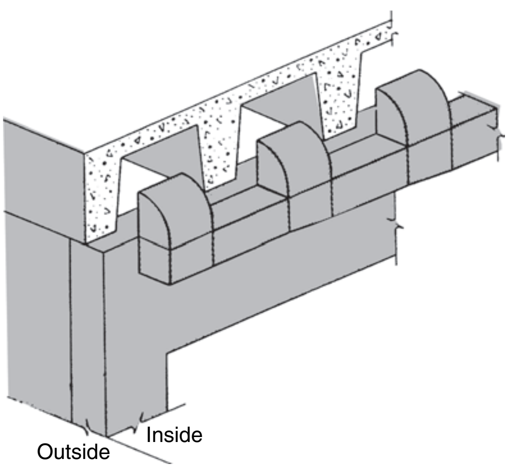
STEP 1. In column II of Table 10.5, list the hourly outdoor temperatures for the design condition (these may be approximated from the summer DB temperature and mean daily range). This will give the worst-day performance. (To get average-day performance, list average hourly temperatures, which are available from local weather service records.) You need not list temperatures above 80°F (27°C) because outdoor air will not be used for cooling above that temperature. (The information assembled in Table 10.5 and subsequent steps using I-P units can also be developed using SI units.)

STEP 2. Calculate the 24-hour heat gain for the building in Btu. Find the sum of all the hourly heat gains through the envelope, the minimum ventilation while "closed," and the internal gains while operating. List on line H of Table 10.5.

STEP 3. Find the total area of the thermal mass surface that is *exposed* (no rugs, etc.) both to the space to be cooled *and* to moving night air during the ventilation ("open") cycle; list on line A of Table 10.5. Note: The larger the mass area exposed, the better the performance. This is why direct-gain solar-heated buildings, with plentiful exposed mass, often make such good candidates for night ventilation cooling. Two additional comments on mass surface: Place it where people "see" it so that it can readily receive their radiant heat, and keep direct sun off the mass (and out of the building) during the cooling season.

STEP 4. Find the mass heat capacity for the entire space to be cooled: mass volume × density × specific heat. Table E.1 lists both density and specific heat for most common building materials; Table 10.6 shows a quick way to get mass heat capacities for the most common thermal mass materials. Enter this total mass heat capacity on line B of Table 10.5.

STEP 5. For "supplementary" cooling due to surfaces *other* than those of the principal thermal



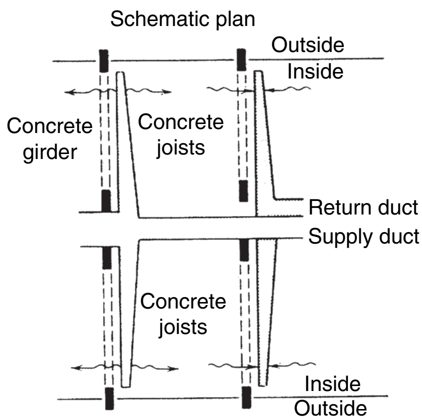


Fig. 10.23 Example of ductwork for night ventilation using the thermal mass of a concrete structural system.

TABLE 10.5 Night Ventilation of Thermal Mass

Calculation Procedure

A. Mass surface area (from step 3) ____________ ft^2
B. Mass heat capacity (from step 4) ____________ Btu/°F
C. Floor area (supplementary cooling, step 5), and total building volume ____________ ft^2 ____________ ft^3

(I) Hour	(II) Outside Air Temperature (°F)	(III) Cooling (Btu)	(IV) Mass Temperature (°F)
8:00 P.M.	______	______	______
9:00 P.M.	______	______	______
10:00 P.M.	______	______	______
11:00 P.M.	______	______	______
Midnight	______	______	______
1:00 A.M.	______	______	______
2:00 A.M.	______	______	______
3:00 A.M.	______	______	______
4:00 A.M.	______	______	______
5:00 A.M.	______	______	______
6:00 A.M.	______	______	______
7:00 A.M.	______	______	______
8:00 A.M.	______	______	______
9:00 A.M.	______	______	______

D. Total mass cooling ____________ Btu ____________ °F
E. Final mass temperature ____________ °F
F. Supplementary cooling (see steps 5 and 11) ____________ Btu
G. Total cooling, D + F ____________ Btu
H. 24-hr heat gain, from step 2 ____________ Btu
I. Flow rate required for night ventilation ____________ cfh or ____________ ACH

mass, list the space's *floor area*. This step should be taken only for spaces with a significant amount of roof, wall, or floor area *in addition* to the thermal mass areas counted in step 3. For example:

- If the space has exposed concrete ceilings, walls, and floors—all counted already as thermal mass—skip this step.
- If all thermal mass is in the form of free-standing water containers, enter the entire floor area.
- If the entire ceiling is thermal mass, but the walls or the floors are not, enter half of the floor area.
- If the entire ceiling is thermal mass, but the floor is not, and there are few or no walls (e.g., open office plan), enter one-third to one-fourth of the floor area.

STEP 6. Complete column III hour by hour after determining the mass temperature (column IV for the preceding hour):

$$\text{cooling Btu/h} = \left[\begin{array}{l} \text{Previous hour mass temp., °F (col. IV)} \end{array} - \begin{array}{l}\text{outside temp., °F (col. II)}\end{array}\right] \times \begin{array}{c}\text{mass surface area, ft}^2\\ \text{(line A)}\end{array} \times \begin{array}{c}\text{surface conductance,}\\ \text{Btu/h ft}_2\text{°F}\end{array}$$

TABLE 10.6 Common Mass Heat Capacities

I-P Units $ft^3 \times (Btu/ft^3\ °F) = Btu/°F$		*SI Units* $m^3 \times (kJ/m^3K) = kJ/K$
Volume × (62.4)	Water	Volume × (4181)
Volume × (22.5)	Ordinary concrete	Volume × (1507)
Volume × (18.7)	Masonry, grout-filled	Volume × (1253)
Volume × (15.6)	Brick	Volume × (1045)

Source: Adapted from Crowther, "Night Ventilation Cooling of Mass," in Miller (1980).

For the first hour, assume that the mass temperature is 80°F. The surface conductance is usually assumed as 1.0 Btu/h ft^2 °F. (See Table E.3 for other surface conductances under various conditions, many of which are considerably more than 1.0.)

STEP 7. Complete column IV, hour by hour, after calculating the cooling Btu/h (column III):

$$\text{mass temp.} = \text{previous hour mass temp. (col. IV)} - \frac{\text{cooling Btu/h (col. III)}}{\text{mass heat capacity, Btu/°F (line B)}}$$

STEP 8. Continue this hourly process using columns III and IV *until* the falling temperature of the mass equals the rising temperature of the outdoor air. At that point, continuing with plentiful ventilation will only rob the mass of its coolth; the building therefore switches to (thermally) closed mode, with minimal ventilation.

STEP 9. Add all the hourly cooling Btu/h values (column III) to obtain the total mass cooling in Btu (line D).

STEP 10. Note the final mass temperature from column IV. This is probably at least 5F° *above* the *lowest* air temperature of the night (column II). If this lowest mass temperature is significantly higher, consider redesigning for more exposed mass surface area.

STEP 11. If supplementary cooling is appropriate (see step 5), calculate it as follows:

$$\text{supplementary cooling, Btu} = \left[80°\text{F} - \begin{matrix}\text{final mass}\\ \text{temperature}\\ \text{(line E)}\end{matrix}\right] \times 2.25 \times \left[\begin{matrix}\text{floor area}\\ \text{(line C)}\end{matrix}\right]$$

The factor 2.25 assumes a modest role for the other, less thermally massive surfaces. Enter this supplementary cooling on line F.

STEP 12. Obtain total cooling by adding lines D and F; enter the total on line G.

STEP 13. In step 2, you entered the 24-hour heat gain for the building on line H. Compare this required cooling to the total cooling provided (line G). If you have not provided enough cooling, and the final mass temperature is more than 7F° above the lowest nighttime outdoor temperature, consider redistributing the building mass over a wider surface (e.g., 3000 ft^2 of 4-in. slab rather than 2000 ft^2 of 6-in. slab) and trying again. If you do not have enough cooling, and the final mass temperature is 5 to 7F° above the lowest nighttime outdoor temperature, consider providing *both* more mass and more surface area (e.g., 3000 ft^2 of 4-in. slab rather than 2000 ft^2 of 4-in. slab) and trying again.

STEP 14. Determine and enter on line I the approximate flow required for night-ventilating air. Use the following formula:

$$\text{cfh} = \frac{\text{Btu/h}}{0.018\Delta t}$$

where

cfh (ft^3/h) = the minimum required flow rate of night air
Btu/h = the cooling Btu for the hour of maximum cooling during the night (column III)
Δt = the temperature difference between the final mass temperature (column IV) and the outdoor air (column II) for that same hour of maximum cooling

It is often useful to express this night ventilation flow rate in terms of ACH:

$$\text{ACH} = \frac{\text{cfh required}}{\text{building volume (ft}^3\text{)}}$$

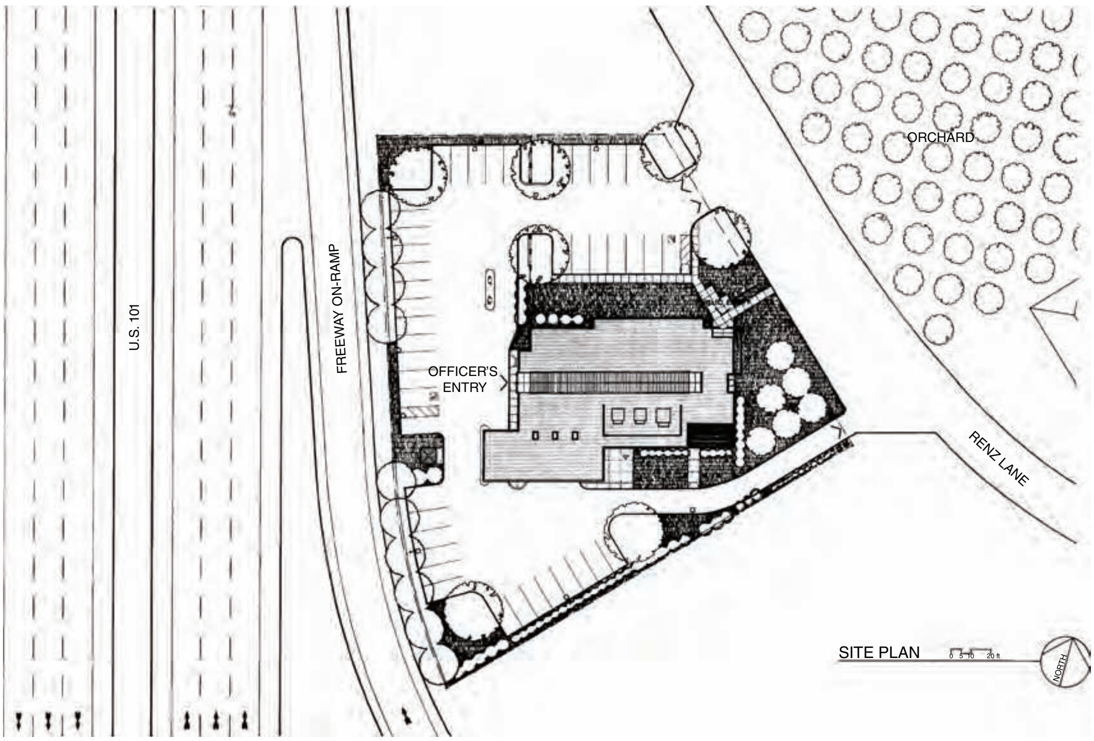
Another night ventilation example is the California Highway Patrol offices at Gilroy, California, shown in Fig. 10.24. This one-story building sits near a freeway interchange south of San José. In this building, the nighttime air is drawn in as far from the freeway as possible, taken underground a short distance (with just a bit of earth tube cooling), then distributed throughout the central corridor. At either end of a continuous skylight over the central corridor, large fans exhaust air by night. Corridor walls are concrete block, and the floor is a concrete slab on grade. The cool night air may carry a seasonal scent; Gilroy calls itself the garlic capital of the world.

(d) Fan-Assisted Evaporative Cooling

Before beginning the following calculations, be sure that:

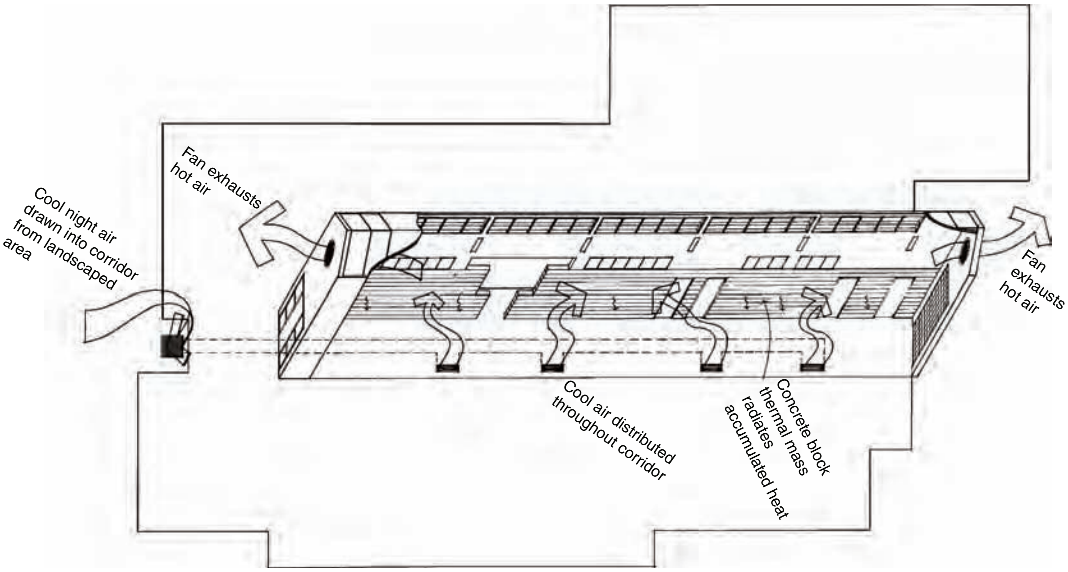
1. You have checked your summer climate against the passive cooling design strategies (Fig. 10.2), and the evaporative cooling strategy is appropriate.

(*a*)



(*b*)

Fig. 10.24 *The California Highway Patrol building near Gilroy, California (a) is flushed with night air for cooling. (b) Site plan. (c) Axonometric shows intake air through a very short earth tube; night flush exhausts are at either end of the central skylit corridor with thermally massive walls and floor. (d) Looking up at one night flush exhaust duct. (e) Exterior with night flush exhaust grille. (Drawings courtesy of The Colyer/Freeman Group, San Francisco.)*



(*c*)

(*d*)

(*e*)

Fig. 10.24 *(Continued)*

2. Your building and climate have been checked for approximate performance based on the design guidelines for evaporative cooling (Section 10.4*d*).

First, find the total sensible heat gain in Btu/h that is to be removed from your building by evaporative cooling. Generally, this is calculated at your climate's summer design DB and mean coincident WB temperatures (Table B.1). The psychrometric chart is then used to plot the progress of evaporatively cooled air, as shown in Fig. 10.25. (The complete psychrometric chart is given in Fig. G.1 [I-P units].)

STEP 1. Determine outdoor air conditions. Enter the psychrometric chart at the summer design DB and mean coincident WB temperatures for your climate (point *A* in Fig. 10.25). As the air is blown through the evaporative cooler, it proceeds along the constant WB line toward saturation or 100% RH (from point *A* toward point *B* in Fig. 10.25).

STEP 2. Determine supply air temperature. The most efficient evaporative cooler will be able to cool and humidify the outdoor air to a point *about three-fourths* of the total distance on the chart from entering air conditions to saturation (the three-fourths point is reached at point *B* in Fig. 10.25); a more reasonable operating assumption may be two-thirds of that total distance.

STEP 3. Determine Δt indoors. At conditions of point *B*, the air leaves the evaporative cooler and

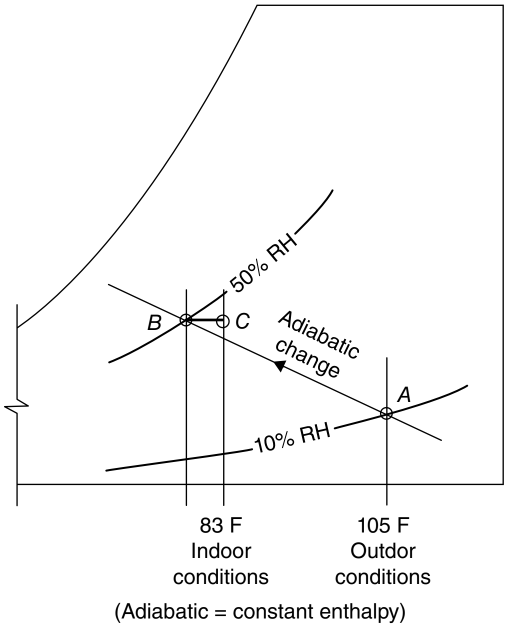


Fig. 10.25 *Once-through cycle of outdoor air through a fan-forced evaporative cooler. Values are transcribed from the psychrometric chart (Fig. G.1). Hot, dry air can be humidified adiabatically (no change in total heat content) from point A to point B, reaching indoor conditions that fall within, or close to, the optimum comfort zone shown in Chapter 4. This is accomplished without the use of the high-energy-consuming compressive refrigeration cycle. As the humidified air picks up sensible heat from the space, it moves from point* B *to point* C.

enters the building. It immediately begins to pick up sensible heat (moving from point *B* toward point *C* in Fig. 10.25). When the air has picked up enough heat to reach a marginally warm temperature, it is exhausted to the outdoors (point *C* in Fig. 10.25). Note, however, that this exhaust air is still well below outdoor temperatures, and therefore is capable of some cooling just outside the building.

STEP 4. Calculate heat removed and airflow rate indoors. The heat removed from the building by this airflow depends on two factors: (1) the DB temperature difference (Δt) between the supply air and the exhaust air (point *B* to point *C* in Fig. 10.25) and (2) the airflow rate usually expressed in cubic feet per minute (L/s):

$$\begin{aligned}\text{Btu/h removed} &= (\text{cfm airflow})\\ &\times (1.1 \text{ Btu min/ft}^3\ {}^\circ\text{F h})\\ &\times (\Delta t, \text{F}^\circ)\end{aligned}$$
$$[\text{SI: W} = (\text{L/s})(1.2)(\Delta t,\ \text{C}^\circ)]$$

The designer can vary the airflow rate by choosing larger or smaller evaporative coolers; any point less than three-fourths of the total distance from outdoor air to saturation may also be chosen.

EXAMPLE 10.9 A 4000-ft^2 (279-m^2) retail store near Tucson, Arizona, has been calculated to have a total sensible heat gain of 100,000 Btu/h (29,310 W) at summer design conditions (105°F DB, 66°F WB [40.6°C, 18.9°C] for this location, from local climate data). How many evaporative coolers are needed to remove heat gains?

SOLUTION

STEP 1. Enter Fig. 10.25 at 105 DB, 66 WB (or equivalent SI values), shown as point *A*.

STEP 2. Measure along the constant 66-WB line to saturation, and determine that three-fourths of this distance corresponds to 76 DB, 66 WB (point *B*).

STEP 3. Δt indoors depends on the assumed exhaust air DB temperature; assume 83°F in this example (point *C*, corresponding to 83 DB, 68 WB). Then, $\Delta t = 83 - 76 = 7\text{F}^\circ$.

STEP 4. Calculate heat removed and airflow rate indoors.

$$\begin{aligned}100{,}000 \text{ Btu/h removed} &= (\text{cfm airflow})\\ &\times (1.1 \text{ Btu min/ft}^3\ {}^\circ\text{F h})\\ &\times (7\text{F}^\circ)\end{aligned}$$

Rearranging the equation yields

$$\begin{aligned}\text{cfm} &= \frac{100{,}000 \text{ Btu/h}}{1.1 \text{ Btu min/ft}^3\ {}^\circ\text{F h} \times 7\text{F}}\\ &= 12{,}987 \text{ cfm } (6130 \text{ L/s})\end{aligned}$$

Note that this is a rate of 12,987/4000 = 3.3 cfm/ft^2 of floor area (16.8 L/s m^2).

This airflow rate can be provided by one larger or several smaller cooling units, depending on possible zoning of the building. For instance, two evaporative coolers at 7000 cfm (3303 L/s) each would meet the requirements for this retail store; one might serve a smaller-area zone in front with show windows and a lot of solar gain, while another might serve a larger-area interior zone with less solar gain. ■

(e) Cooltowers

One of the first North American cooltowers was shown in Fig. 10.11, along with estimated cooling design guidelines in Fig. 10.12. To more closely estimate the performance of such a passive evaporative device with calculations, some very complex equations are involved (for example, see Thompson et al., 1994). For a shorter but less-exact approach, consider this formula proposed by Givoni (1994) in either °F or °C:

$$t_{exit} = \mathrm{DB} - 0.87\,(\mathrm{DB} - \mathrm{WB})$$

where
t_{exit} = air entering the space (exiting the cooltower)
DB = dry-bulb temperature, outside
WB = coincident wet-bulb temperature, outside

This simple equation ignores the potential influences of both wind (driving more air through the evaporative cooling pads) and the optional solar chimney exhaust tower (seen in Fig. 10.11).

Cooling achieved by the tower depends both on the temperature of this exit air and on its flow rate. Givoni (1994) proposes, in SI units:

$$V = 0.033\, A_{evap} \sqrt{H(\mathrm{DB} - \mathrm{WB})}$$

where
V = flow, in m^3/s (× 1000 = L/s)
A_{evap} = total area of wetted pads, m^2, in cooltower
H = overall height of tower, m
DB = dry-bulb temperature, outside
WB = coincident wet-bulb temperature, outside
0.033 = accounts for pressure drop through the tower and the building

Note that this equation ignores the area of both the cooltower and the outlet. Knowing both the temperature and the flow rate, the cooling capacity achieved is

$$W = 1.2\ V\,[t_{int} - t_{exit}]$$

where
W = watts removed from space by cooltower
V = flow from cooltower, in m^3/s (× 1000 = L/s)
t_{int} = DB temperature to be maintained indoors, C
t_{exit} = air entering the space (exiting cooltower), C

In I-P units, this becomes

$$V = 2.7\, A_{evap} \sqrt{H(\mathrm{DB} - \mathrm{WB})}$$

where
V = flow, in cfm
A_{evap} = total area of wetted pads, ft^2, in cooltower
H = overall height of tower, ft
DB = dry-bulb temperature, outside, F
WB = coincident wet-bulb temperature, outside, F
2.7 = accounts for pressure drop throughout the tower and the building

Note that this equation ignores the area of both the cooltower and the outlet. Knowing both the temperature and the flow rate, the cooling capacity achieved is

$$\mathrm{Btu/h} = 1.1\,\mathrm{V}\,[t_{int} - t_{exit}]$$

where
Btu/h = heat removed from space by cooltower
V = flow from cooltower, in cfm
t_{int} = DB temperature maintained indoors, F
t_{exit} = air entering space (exiting cooltower), F

In a remote desert west of Tucson, Arizona, the Agua Blanca ranch uses several cooltowers to serve a building around a T-shaped courtyard (Fig. 10.26). This off-grid building complex uses PV for lighting and water pumping, propane for a refrigerator, and one wall heater and stand-by generator, and collects rainwater in a cistern below the courtyard. Wood stoves and fireplaces supplement direct solar gain in winter. The courtyard connects to the surrounding ranch by three passages, one covered with a roof and small open skylights, one covered with a deciduous vine on a trellis, and one open to the sky. Large rolling barn doors are located at the outer end of each passage; these provide both security and the ability to trap cool air from the cooltowers (or via the indoor spaces), thus increasing hot-weather comfort outdoors.

Three cooltowers, 22 ft (6 m) high, each with a total evaporative pad area of 64 ft^2 (5.9 m^2), serve three units around the courtyard. At the outlet of each cooltower, the cool airflow can be controlled: shared or sent to either of two locations, or closed off. One of the cooltowers can deliver air directly to the covered passage off the courtyard.

Design simulations (Yoklic and Layseca, 1998) for a typical June in Tucson predict a flow from each cooltower of about 5000 cfm (2360 L/s), maintaining the indoor temperature at 74°F (23.3°C). In these quite small buildings, this translates into an ACH of about 60, considering the volume to include

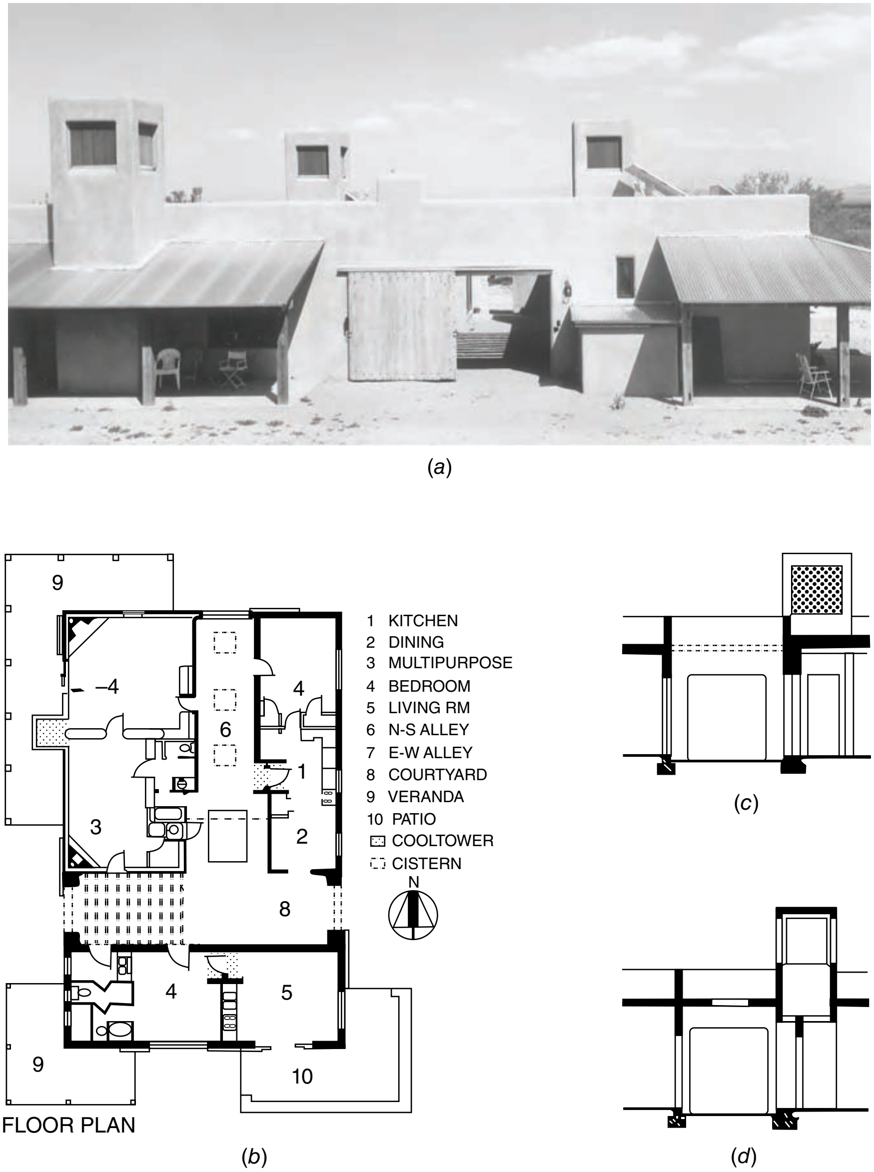


Fig. 10.26 *Cooltowers dominate the silhouette of the Agua Blanca ranch in a remote desert near Tucson, Arizona. (a) West side, with one of the large rolling barn doors that allow the courtyard/outdoor spaces to be connected with cooler breezes or to be protected from hot winds. Air from the cooltowers, after use within the units, can be discharged to the courtyard, while (under the hottest conditions) it is still cooler than outdoor air. This helps to form a "cool pool" of air in the protected courtyard. (b) Plan of three units, each with a cooltower, around a T-shaped courtyard/covered passage outdoor space. (c) East–west section through the courtyard. (d) North–south section through one of the three cooltowers. (Courtesy of Martin Yoklic, Environmental Research Laboratory, University of Arizona.)*

a height up to 6 ft (1.8 m), above which stratification of warm air negates circulation through the upper portion of the space.

These computer-generated design simulations are summarized in Table 10.7. These results differ somewhat from the results of Givoni's (1994) equations, suggesting that perhaps in this case:

$$t_{\text{exit}} = \text{DB} - 0.70\,[\text{DB} - \text{WB}]$$

and that the flow rate (in SI units) may be closer to

$$V = 0.04\,A_{\text{evap}}\,\sqrt{2z\,(\text{DB} - \text{WB})}$$

TABLE 10.7 Cooltower Performance Hourly Simulations[a]

Ambient (°F)			Tower Outflow					Ambient (°C)			Tower Outflow				
DB	WB	RH (%)	DB	RH (%)	Velocity (fpm)	Flow Rate (cfm)	Water Consumed (gal/h)	DB	WB	RH (%)	DB	RH (%)	Velocity (m/s)	Flow Rate[c] (m^3/s)	Water Consumed (L/h)
PART A. TOWER EFFECTIVE HEIGHT[b] = 10 ft (3 m)															
82	56	18.2	61.6	72.0	170	4254	9.8	27.8	13.3	18.2	16.4	72.0	0.86	2.00	37.1
87	59	18.0	65.1	71.0	175	4384	10.8	30.6	15	18.0	18.4	71.0	0.89	2.07	40.9
93	62	16.7	68.9	69.1	183	4572	12.3	33.9	16.7	16.7	20.5	69.1	0.93	2.16	46.6
98	64	15.0	71.8	67.0	190	4752	13.9	36.7	17.8	15.0	22.1	67.0	0.97	2.24	52.6
102	64	11.4	72.9	63.2	199	4987	16.1	38.9	17.8	11.4	22.7	63.2	1.01	2.35	60.9
PART B. TOWER EFFECTIVE HEIGHT[b] = 15 ft (4.6 m)															
82	56	18.2	62.2	69.6	205	5133	11.5	27.8	13.3	18.2	16.8	69.6	1.04	2.42	43.5
87	59	18.0	65.7	68.7	212	5289	12.7	30.6	15	18.0	18.7	68.7	1.08	2.50	48.1
93	62	16.7	69.6	66.7	221	5516	14.4	33.9	16.7	16.7	20.9	66.7	1.12	2.60	54.5
98	64	15.0	72.5	64.5	229	5734	16.3	36.7	17.8	15.0	22.5	64.5	1.16	2.71	61.7
102	64	11.4	73.7	60.5	241	6017	18.9	38.9	17.8	11.4	23.2	60.5	1.22	2.84	71.5
PART C. TOWER EFFECTIVE HEIGHT[b] = 20 ft (6.1 m)															
82	56	18.2	62.6	68.0	235	5864	12.9	27.8	13.3	18.2	17.0	68.0	1.19	2.77	48.8
87	59	18.0	66.2	67.0	242	6043	14.2	30.6	15	18.0	19.0	67.0	1.23	2.85	53.7
93	62	16.7	70.1	65.0	252	6302	16.1	33.9	16.7	16.7	21.2	65.0	1.28	2.97	60.9
98	64	15.0	73.0	62.7	262	6550	18.2	36.7	17.8	15.0	22.8	62.7	1.33	3.09	68.9
102	64	11.4	74.3	58.7	275	6874	21.1	38.9	17.8	11.4	23.5	58.7	1.40	3.24	79.9

Source: Excerpted from Yoklic and Layseca (1998). Additional simulations courtesy of Martin Yoklic. SI conversions by the authors of this book.

[a]Tower has a total evaporative pad area of 64 ft^2 (5.95 m^2); pad thickness is 4 in. (100 mm); tower outlet area is 25 ft^2 (2.32 m^2); building outlet area is 50 ft^2 (4.65 m^2). Ambient data are selected from Tucson, Arizona, typical June.

[b]Effective height is measured from the bottom of the evaporative pads to the top of the outlet to the building.

[c]Flow rate (m^3/s) × 1000 = L/s.

where z = effective height of the tower, that is, from the bottom of the evaporative pads to the top of the outlet to the building.

(f) Roof Pond Cooling

Before doing the following detailed calculations, be sure to (1) check the summer climate against the passive cooling design strategies (Fig 10.2) to confirm that either the evaporative or the high thermal mass strategy is appropriate, and (2) check the building and climate for approximate performance based upon the design guidelines. Note, however, that the design guidelines are based *only* on summer night DB temperature. With evaporative cooling (such as a light spray onto the surface of the roof pond containers), better performance can be expected, as shown by the following calculation procedure, based on Fleischhacker et al. (1982). This procedure can be used to check the size and depth required for an acceptable building roof pond. It assumes an *optimum pond depth of 4 in.* (*100 mm*) but allows for other depths as well. The procedure is presented in I-P units, but can be conducted in SI by appropriate conversions.

STEP 1. First, assemble the following data on the site climate (shown in I-P units for this example):

Maximum DB temperature (Appendix B)
Mean daily range (Appendix B)
Minimum DB temperature (= maximum DB – mean daily range)
Design WB (2%) (Appendix B)
Average maximum RH for July (from local climatological data)
July average temperature (TA July in Appendix C)

From these data, determine two further characteristics for the climate of the site: (1) minimum WB temperature and (2) average July operating hours for residential air conditioning, or *N*.

Minimum WB temperature can be determined from the psychrometric chart (shown in Figs. G.1 and G2). Enter the chart with minimum DB and move vertically along the constant DB line until reaching the average maximum RH for July. At that intersection, refer to the diagonal WB temperature lines, from which minimum WB temperature can be determined (Fig. 10.27).

Average July operating hours, N, can be estimated from Fig. 10.28. Enter at July TA for the site climate. The climate's *N* will fall somewhere between the maximum *N* and minimum *N* lines; as a guide to estimating *N* for the climate, compare the climate's mean daily range and design WB to those of the cities shown in Fig. 10.28. The higher the mean daily range and the lower the design WB, the lower the *N*.

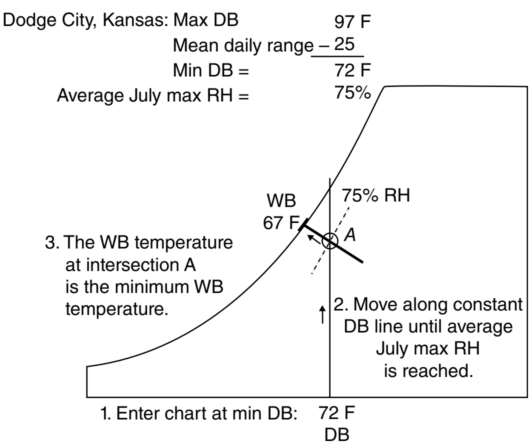


Fig. 10.27 *Finding the minimum (nightly) WB temperature, summer design conditions, for Dodge City, Kansas.*

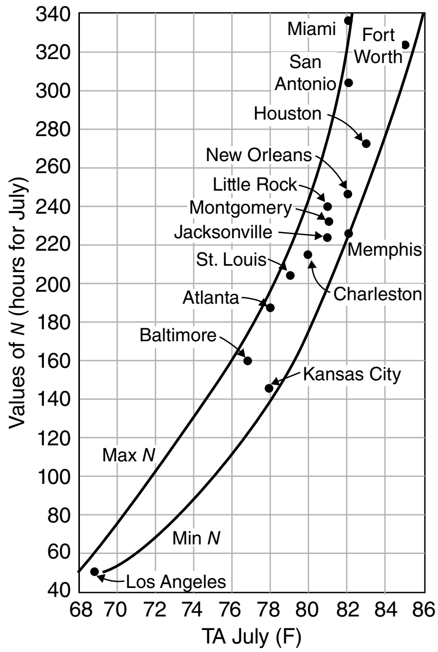


Fig. 10.28 *Range of* N*, average July operating hours, for residential air conditioners. (Based on Fleischhacker et al., 1982.)*

STEP 2. Calculate the peak hourly heat gain *but exclude internal gains*. (The method given in Section 10.6 is appropriate for this roof–pond-sizing procedure.)

STEP 3. Approximate the daily total heat (excluding internal heat) to be stored in the roof pond, or Q_E, in Btu:

$$Q_E = \frac{\text{(Btu/h, peak hourly gain)} \times (N\text{, hours for July)}}{\text{31, days in July}}$$

STEP 4. Determine the rate of the internal gain, in Btu/h, while the building is occupied.

STEP 5. Approximate the daily total internal heat to be stored in the roof pond, Q_I, in Btu.

$$Q_I = \text{hourly internal gains, in Btu/h} \times \text{daily hours of building occupation}$$

STEP 6. Calculate the daily heat gain directly to the roof pond through its insulated covers, Q_P, in Btu. This formula assumes R-16 (SI: R-2.8) insulating panels with white upper surfaces and foil faces on the under surface.

$$Q_P = 0.4(A_c)(4 \times \text{DB max} - \text{DB min} - 200)$$

where A_c is the horizontal surface area of pond in square feet and temperatures are in °F.

STEP 7. Consider whether fans will be used to stir the room air below the roof pond (to help the heat exchange between the pond and the room, as well as to provide comfort), and determine the value to be used for h, the overall heat transfer coefficient. A corrugated steel deck ceiling is assumed.

Air Velocity	fpm (m/s)	0 (0)	44 (1.22)	73 (0.37)	115 (0.6)
Value of h		1.25	1.47	1.53	1.70

STEP 8. Determine the highest comfortable internal air temperature, t_{op}, from the comfort criteria provided in Fig. 4.16.

STEP 9. Calculate the maximum allowable internal air temperature, t_{imax}, which will be higher than t_{op} by a factor F that is related to your climate's characteristics (see Table 10.8, Part A, for values of F).

$$t_{imax} = t_{op} + F$$

STEP 10. Determine the allowable temperature swing of the roof pond.

(a) Calculate the maximum pond t:

max. pond $t =$

$$t_{imax} - \frac{\begin{pmatrix}\text{peak hourly heat gain} \\ \text{including internal heat gains, Btu/h}\end{pmatrix}}{h\,(A_c)}$$

where t_{imax} is from step 9, h is from step 7, and A_c is the horizontal surface area of the pond in square feet.

(b) Calculate the minimum pond t, which depends on whether evaporative cooling will be used to help lower the pond's temperature and on several characteristics of the pond and the building.

1. For a dry pond surface:

min. pond $t_{dry} = DB_{min} + 1.5F° \pm$ corrections F° (if any, from Table 10.8 Part B)

2. For a wet pond surface:

$$\text{min. pond } t_{wet} = DB_{min} - \frac{DB_{min} - WB_{min}}{2}$$

(c) Find the pond temperature swing Δt_p:

$$\Delta T_{pdry} = \text{max. pond } t - \text{min. pond } t_{dry}$$
$$\Delta T_{pwet} = \text{max. pond } t - \text{min. pond } t_{wet}$$

(Obviously, if neither minimum pond t dry nor minimum pond t wet is lower than maximum pond t, a roof pond cannot be used for cooling.)

STEP 11. Determine the required pond depth D (in inches).

$$D = \frac{(0.19)\,(Q_E + Q_I + Q_P)}{(\Delta t_p)\,(A_c)}$$

where Q_E, Q_I, and Q_P are the daily pond heat gains from steps 3, 5, and 6; Δt_p is from step 10; and A_c is the horizontal surface area of the pond in square feet.

TABLE 10.8 Roof Pond Design Data

PART A. VALUES OF FACTOR "F"				
			"F," Based on Interior Air Motion	
Location	Design DB/Mean Coincident WB °F (°C)	MDR °F (°C)	None	Fans: 115 fpm (0.6 m/s)
Miami, Florida	90/77 (32.2/25)	15 (8.3)	2.0	1.0
San Antonio, Texas	97/73 (36.1/22.8)	19 (10.6)	3.0	1.5
Phoenix, Arizona	107/71 (41.7/21.7)	27 (15)	4.0	2.0

PART B. CORRECTIONS TO MINIMUM (DB) POND TEMPERATURE, F° (C°)											
				Night Internal Load							
Pond Depth in. (mm)				Btu/h ft² (W/m²)				Pond Portion Exposed to Sky			
2 (50)	4 (100)	6 (150)	10 (250)	0 (0)	2 (6.3)	4 (12.6)	8 (25.2)	⅓	½	⅔	Fully
–1.5 (–0.8)	+0 (+0)	+0.7 (+0.4)	+1.0 (+0.6)	+0 (+0)	+0 (+0)	+0.8 (+0.4)	+2.5 (+1.4)	+3.3 (+1.8)	+2.1 (+1.2)	+1.2 (+0.7)	+0 (+0)

Source: Fleischhacker et al. (1982). SI units added.

Note: If D is less than 4 in., consider reducing the pond size and recalculating. If D is much more than 4 in., consider a larger pond area, more air motion indoors, the use of a wet pond surface to more closely approach the optimum 4-in. depth, or see optional step 12.

STEP 12. (optional) Auxiliary mechanical air conditioning may offer a more economical alternative than increased pond size. The size, in tons (12,000 Btu/h) of air co nditioning required, is determined as follows:

(a) desired D is 4 in. optimum.

(b) $\Delta t_p = \left(\frac{0.19}{D}\right)\frac{(Q_E + Q_I + Q_P)}{A_c}$

(c) so max. pond t = min. pond $t + \Delta t_p$

(d) and tons of AC at peak total hourly heat gain =

$$= \frac{(\text{Btu/h} - [h\,(A_c)]\,(t_{i\max} - \text{max pond } t)}{12{,}000}$$

where the peak total hourly heat gain *includes* internal gains, h is from step 7, A_c is the horizontal surface area of the pond in square feet, $t_{i\max}$ is from step 9, and max. pond t is from step 10.

EXAMPLE 10.10 (extended from EXAMPLE 10.5) What size should the roof pond be for the Albuquerque office building for which we predicted that a 4-in.-deep (100 mm) pond equal to three-fourths of the building's floor area would be sufficient? Assume that the one-story office is about 4000 ft^2 (372 m^2) in area. Try a 4-in.-deep (100 mm) pond of 3000 ft^2 (279 m^2).

SOLUTION

STEP 1. Albuquerque, design data:

DB_{max} is 91°F (32.8°C) (Table B.1).

MDR is 25.3F° (14.1C°) (Table B.1).

DB min. is 91 – 25.3 = 66°F (18.9°C).

July RH maximum (nighttime) is approximately 50% (local data).

July TA is 79°F (26.1°C) (Appendix C).

WB_{min} is from Fig. G.1; at the intersection of the 66°F DB and 50% RH, this is 55°F (12.8°C).

July operating hours N for this dry, high area should be close to the minimum for TA = 79° F (26.1°C); from Fig. 10.28, this is about 160 hours.

STEP 2. Determine the peak hourly gain. Earlier in this exercise, a total gain of 15 Btu/h ft^2 (47.3 W/m^2) was assumed as an average. Assume that 9 Btu/h ft^2 (28.4 W/m^2) of this total represents the load from electric lighting, people, and equipment, and that 6 Btu/h ft^2 (18.9 W/m^2) is due to envelope and ventilation gains. (No heat gains to the interior are assumed through the roof pond.) Then peak hourly gains (excluding internal)

$$= 6 \times 4000 \text{ ft}^2 = 24{,}000 \text{ Btu/h (7035 W)}$$

STEP 3.

$$Q_E = \frac{24{,}000 \text{ Btu/h} \times 160 \text{ h}}{31 \text{ days}}$$
$$= 123{,}870 \text{ Btu (36.3 kWh)}$$

STEP 4.

$$\text{internal gains} = 9 \text{ Btu/h ft}^2 \times 4000 \text{ ft}^2$$
$$= 36{,}000 \text{ Btu/h (10,550 W)}$$

STEP 5.

$$Q_I = (36{,}000 \text{ Btu/h})(9 \text{ hours of operation})$$
$$= 324{,}000 \text{ Btu (95 kWh)}$$

STEP 6.

$$Q_p = 0.4(3000 \text{ ft}^2)\,(4 \times 91°\text{F} - 66°\text{F} - 200)$$
$$= 1200 \times (364 - 66 - 200)$$
$$= 1200 \times 98 = 117{,}600 \text{ Btu (34.5 kWh)}$$

STEP 7. Fans will be used, at 115 fpm (0.6 m/s), for added comfort as well as for heat transfer. Therefore, $h = 1.7$.

STEP 8. From Fig. 4.9, with 115 fpm (0.6 m/s) air speed, it appears that 83°F (28.3°F) is just within the comfort zone. So, t_{op} = 83°F.

STEP 9. $t_{i\max} = t_{op} + F$. In Table 10.8, Part A, Albuquerque's conditions appear to be somewhere between those of San Antonio and those of Phoenix, so assume F to be 1.75.

$$t_{i\max} = 83 + 1.75 = 84.75°\text{F (29.3°C)}$$

STEP 10.

(a) max. pond $t = t_{i\max} - \frac{\text{total hourly gain}}{h\,(A_c)}$

$$= 84.75 - \frac{24{,}000 + 36{,}000}{1.7 \times 3000}$$
$$= 84.75 - 11.75 = 73°\text{F (22.8°C)}$$

(b) Assume a dry pond surface. Because this is a 4-in.-deep (100 mm) pond that is fully exposed to sky, with no night internal load, there is no correction factor from Table 10.8, Part B.

$$\text{min. pond } t_{dry} = DB_{min.} + 1.5F°$$
$$= 66 + 1.5 = 67.5°F\ (19.7°C)$$

For a wet pond,

$$\text{min. pond } t_{wet} = DB_{min} - \frac{DB_{min} - WB_{min}}{2}$$
$$= \frac{66 - 66 - 56}{2}$$
$$= 61.5°F\ (16.4°C)$$

(c) The pond temperature swing is therefore

$$\Delta t_p \text{ dry} = 73 - 67.5 = 5.5F°\ (3.1C°)$$
$$\Delta t_p \text{ wet} = 73 - 61 = 12F°\ (6.7C°)$$

STEP 11.

$$D_{rqd} = \frac{0.19(123{,}870 + 324{,}000 + 117{,}600)}{5.5 \times 3000}$$
$$= \frac{107{,}439}{16{,}500} = 6.51 \text{ in. (165 mm) for a dry pond}$$

For a wet pond, $D_{rqd} = 3.1$ in. (79 mm) ■

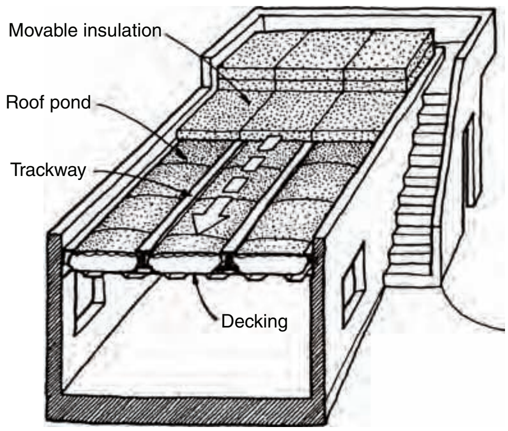
It appears that a 4-in.- (100-mm)-deep pond with a wet surface of somewhat less than 3000 ft^2 (279 m^2) would be sufficient for this building in this climate.

Once the area and the depth of roof ponds have been determined, questions arise about the architectural integration of such large horizontal surfaces and their relative emphasis on heating or cooling. Figure 10.29 shows variations in the treatment of containers and the insulating panels to match the most important thermal role of roof ponds; Fig. 10.30 shows three typical approaches to the placement of roof ponds on buildings. A valuable source of information about the container bags, sliding insulation, roof decks, and other components needed for roof ponds is the *California Passive Solar Handbook* by Phillip Niles and Ken Haggard, written for the California Energy Commission in 1980. Commercially available products include the Skytherm® system, developed and pioneered by Harold R. Hay.

A variation of the roof pond (applying primarily to the cooling mode) is to move the water rather than move the insulation. Water-impervious insulation (such as Styrofoam) is secured in place above the metal ceiling at a distance sufficient to be a reservoir for the cooling water. At night, this water is pumped onto the top of the insulation, where it cools by radiation and evaporation, then trickles slowly back into the reservoir. This variation was tested at the School of Engineering Technology, University of Nebraska at Omaha campus. In winter, the reservoir of water above the metal ceiling acted as thermal mass for a DG passive system. However, cold winter rain must be excluded from that reservoir.

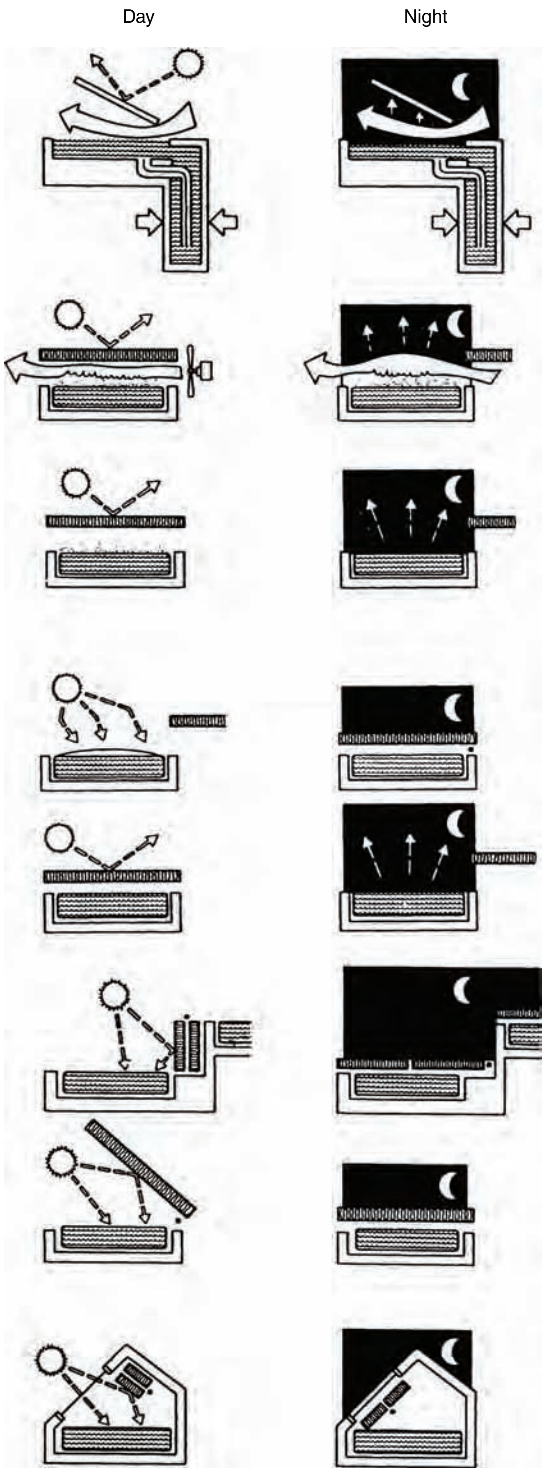
(g) Earth Tubes

The use of the earth as a heat sink, in our culture at any rate, is still in an early development stage. The most direct application would be an underground building with uninsulated concrete walls set against the soil. The problem, of course, is that winter heat loss will likely exceed summer loss; if solar heat can be admitted (e.g., through skylights) to counterbalance the increased winter loss, uninsulated walls sized for the desired summer loss become more attractive. (However, except in dry climates, condensation on walls may pose a seasonal or even year-round problem.) A more thorough discussion of this option can be found in Watson and Labs (1983).



(*a*)

Fig. 10.29 *(a) Key components of roof pond systems with movable insulation. (b–g) Variations on roof ponds for optimization of heating or cooling performance. (Reprinted from Niles and Haggard, 1980, by permission of the California Energy Commission.)*



(*b*) Cooling only

The ponds are shaded from the sun so that cooling can be accomplished by evaporation on a 24-hour basis. Removal of heat from the interior space can be done by radiation and convection to the bottom of the ponds, or by thermosiphoning the cooled water to an interior tank in contact with the room, as shown.

(*c*) Cooling and Some Heating

Flooding the roof ponds adds evaporative cooling to radiation and convection losses. During the day, forcing air over flooded ponds below closed insulation creates additional evaporative cooling.

(*d*) Cooling Emphasis

Flooding the ponds increases cooling through evaporation. Sealed but nonglazed ponds emphasize radiant cooling and are still capable of heating at lower latitudes.

(*e*) Balanced Heating and Cooling

The use of an inflated air cell over the ponds increases heating capability by increasing insulation. During the cooling season, the cell is deflated to allow maximum night sky radiation and convection cooling.

(*f*) Heating Emphasis

The use of lift or bi-fold insulation allows the insulation to also act as a reflector when in the open position, thus increasing solar radiation to the ponds.

(*g*) Maximum Heating and some Cooling

The roof pond is enclosed under a roof that slopes to the north, protecting the ponds from snow and providing permanent insulation on the north side. In the open position, the movable insulation acts as a reflector for low winter sun.

Fig. 10.29 *(Continued)*

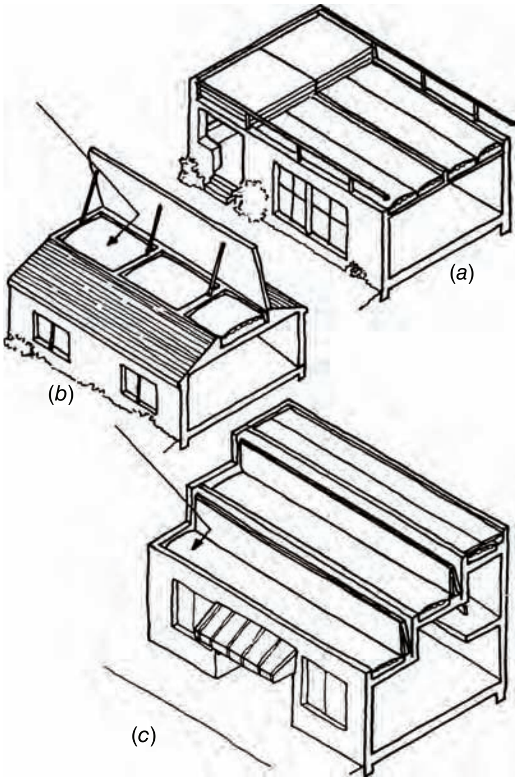


Fig. 10.30 *Three examples of roof pond integration with building form. (a) Insulating panels slide open to stack over exterior (or untempered) space. See Fig. 10.14 for this system in use. (b) Hinged insulating panels with reflective undersurfaces can act as reflectors to increase winter insolation. However, some interference with summer night sky radiation can result, because the pond surface cannot "see" the entire sky dome. (c) Bifold insulating panels also act as reflectors, interfering less with diffuse solar radiation and allowing somewhat more exposure to the night sky than (b). (Adapted from Niles and Haggard, 1980, by permission of the California Energy Commission.)*

The long-term potential of the earth as a heat sink is lessened by the fact that soils are relatively slow heat conductors. For example, we ignore winter heat loss through concrete slabs to the earth below, calculating instead the heat losses through the slab's exposed perimeter.

Earth tubes (as discussed under design guidelines in Section 10.4*g*) are devices for cooling the incoming ventilating air through earth contact before it enters the building. A small amount of air (perhaps equal to the minimum fresh air requirements—see Tables F.1 and F.2) is usually brought in through several tubes. These tubes are usually 8 to 20 in. (200 to 500 mm) in diameter, are buried at a depth of 5 to 10 ft (1.5 to 3 m), and are up to 200 ft (61 m) long. Table G.12 summarizes several tested summertime applications.

The lowest temperature to which air can be cooled in such tubes will *approach* ground temperature; the more slowly the air moves through the tube, the more time there will be for cooling. The air temperature might come within 4F° (about 2C°) of the soil temperature under good conditions.

To approximate soil temperature (in I-P units) around the tube:

1. Determine $t_{GW,}$ the groundwater temperature (in °F) (assumed equal to deep-underground earth temperature) from the map in Fig. 10.31.
2. Determine t_{amp}, the average amplitude of surface temperature (in F°), using the map in Fig. 7.10*c*.
3. Determine CF, the amplitude correction factor, depending upon whether the soil outside the earth tube is dry, average, or wet during the cooling period. The amplitudes, or seasonal variations in earth temperature, *diminish to near zero* at identifiable depths (referred to as CF):

	CF
Dry soil	14 ft (4.25 m)
Average soil	18 ft (5.5 m)
Wet soil	22 ft (6.7 m)

4. Determine D, the depth (ft) at which the earth tube will be installed.
5. Determine t_{SG}, the late summer ground temperature (°F) around the earth tube:

$$t_{SG} = (t_{GW}) + (t_{AMP})[1 - (D/CF)]$$

(Note that when the tube is very deep and $D \geq CF$, $t_{SG} = t_{GW}$.)

6. Determine the temperature difference that makes cooling possible:

$$\Delta t = \text{desired indoor temperature} - t_{SG}$$

7. Determine the long-term cooling rate: Btu/h ft of tube length =

$$(\Delta t)(C)\ (\text{Area of tube surface, ft}^2/\text{ft of length})$$

where C is a factor that accounts for the long-term effects of heat flow from the tube to the soil:

$C = 0.11$ for dry soil
(soil conductivity k = 0.25 Btu/h ft °F)
$C = 0.28$ for average soil (k = 0.75)
$C = 0.44$ for wet soil (k = 1.5)

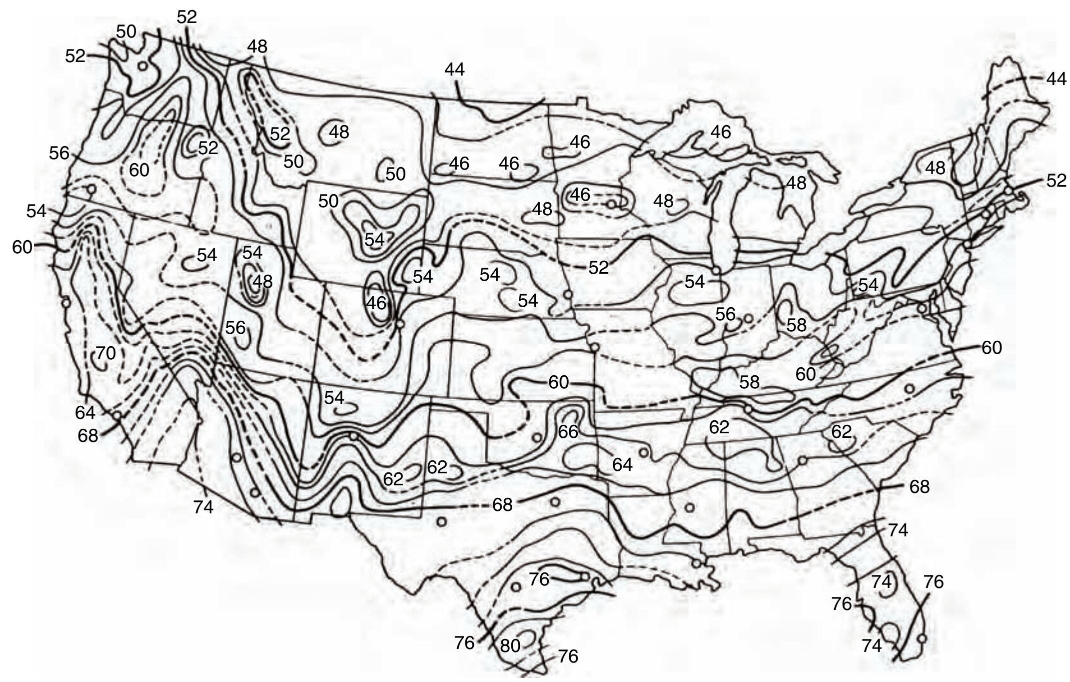


Fig. 10.31 Distribution of well-water temperature (°F) in the United States, adapted from the National Ground Water Association. These temperatures may be assumed to be the yearly average ground temperatures. For seasonal temperature change amplitude, see Fig. 7.10. (Reprinted from Passive Cooling*. 1981. Published by the American Solar Energy Society. Boulder, CO.)*

In SI units,

C = 0.62 for dry soil
C = 1.59 for average soil
C = 2.50 for wet soil

This represents an attempt to simplify a complex problem. The airflow rate is ignored, even though, with very slow flow, there is more time for heat exchange in the tube. The longer the tube is flooded with hot air, the higher will be the earth temperature. For more detailed information about this strategy and other approaches to earth tubes, see Givoni (1994); C. E. Francis, "Earth Cooling Tubes, Case Studies of Three Midwest Installations" in Bowen et al. (1981); Abrams (1986); and Brown et al. (1992).

EXAMPLE 10.11 (Extended from EXAMPLE 10.6)
A partially underground nature center of 4000 ft^2 (372 m^2) in northern Pennsylvania has an hourly heat gain of 9.3 Btu/h ft^2 (29.3 W/m^2), of which 2.2 Btu/h ft^2 (6.9 W/m^2) are due to required outdoor air ventilation. A long trench at a depth of 6 ft (1.8 m) in heavy, damp soil must be dug for a utility connection. If one earth tube, used only for cooling the outdoor ventilation air, is installed at the bottom of the trench, what length and diameter will be needed?

SOLUTION
The total cooling needed from the earth tube is

(4000 ft^2)(2.2 Btu/h ft^2) = 8800 Btu/h (2580 W)

(In Example 10.6, using design guidelines, assuming heavy damp soil, a 60-ft-long tube [18 m], 20 in. [508 mm] in diameter promised to deliver about 4500 Btu/h (1320 W); two such tubes, about 9000 Btu/h (2640 W).)

1. Determine t_{GW}: From Fig. 10.31, northern Pennsylvania has an average underground temperature of 52°F (11.1°C).
2. Determine t_{AMP}: The seasonal amplitude (from Fig. 7.10) is about 18F° (10C°).
3. Determine CF: In wet soil, this amplitude extends to 22 ft (6.7 m).
4. Determine D: The given trench depth is 6 ft (1.8 m).

5. Determine t_{SG}: The late summer ground temperature (working in I-P units) around the earth tube:

$$t_{SG} = (t_{GW}) + (t_{AMP})\,[1 - (D/CF)]$$
$$= (52) + (18)\,[1 - (6/22)]$$
$$= (52) + (13) = \text{about } 65°F\ (18.3°C)\ \textit{at most}.$$

6. Determine the temperature difference that makes cooling possible:

$$\Delta t = \text{desired indoor temperature} - t_{SG}$$

In this case, we accept a maximum 82°F (27.8°C) indoor air temperature (the walls will be cooler, thanks to their underground location), so 82 – 65 = 17F° (27.8 – 18.3 = 9.5C°).

7. Determine (again using I-P units) the long-term cooling rate: Btu/h ft of tube length

$$= (\Delta t)\,(C)\,(A)$$

where, A is area of tube surface, ft^2/ft of length

Here, C = about 0.44 (Btu/h ft^2 F°) for wet soil. Try first the 20-in.- (508-mm)-diameter tube from the earlier design guidelines:

Btu/h ft of tube length

$$= (17F°)(0.44)\left[\frac{20\text{ in.} \times \pi \times 1\text{ ft length}}{12\text{ in./ft}}\right]$$

$$= 39\text{ Btu/h ft}$$

To deliver the full 8800 Btu/h (2580 W), the tube would need to be about 8800/39 = 225 ft (69 m) in length. The design guideline promised considerably more, in this case, than could be delivered.

In early summer, the earth temperature around the tube would be at its yearly average temperature of 52°F (11.1°C). With this larger Δt, 82 – 52 = 30F° (or 16.7C°), the performance improves:

Btu/h ft of tube length

$$= (30F°)(0.44)\left[\frac{20\text{ in.} \times \pi \times 1\text{ ft length}}{12\text{ in./ft}}\right]$$

$$= 69\text{ Btu/h ft}$$

and the tube length under those conditions would be about 8000/69 = 127 ft (39 m). ■

(h) Passive Cooling Summary

As a summary example of a passively cooled and solar-heated building, consider the Visitor Center for the Antelope Valley California Poppy Reserve, about 85 miles (135 km) northeast of Los Angeles (Fig. 10.32). Set in a high desert where winter temperatures sometimes fall below 20°F (–7 °C), the building is 100% passively solar heated by a combination of direct-gain and Trombe wall strategies, interior thermal shades, and thermally massive ceiling, walls, and floor. An earth-sheltered, thermally massive building was chosen for its suitability to the environmentally sensitive site, as well as for its year-round thermal advantage in a desert climate. On summer days when air temperatures frequently exceed 100°F, a combination of an earth tube and evaporative cooling provides a modest supply of fresh air without overheating. Continuous power ventilating of the building at night draws the cool outdoor air through the tube, then over the thermally massive surfaces to provide added cooling capacity for the following day. The 2100-ft^2 (195-m^2) building also is served by an 8-kW wind generator and has its own well.

EXAMPLE 10.12 Use the psychrometric chart to investigate the cooling process at the Antelope Valley Visitor Center. The earth tube is 24 in. (610 mm) in diameter and 150 ft (45.7 m) long, at an average depth of 6 ft (1.8 m).

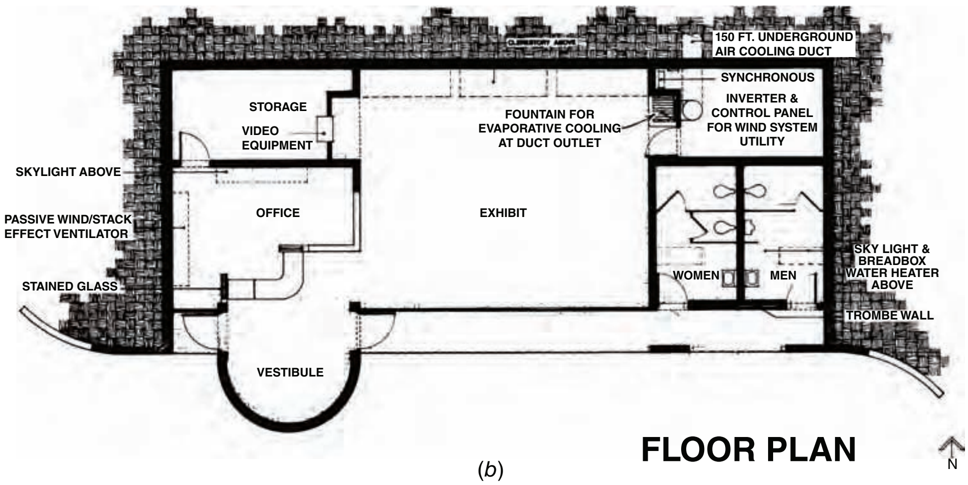
SOLUTION

First, determine the design conditions. Nearby Barstow, California (Table B.5), has a similar climate; the design condition is 104/68 °F, with MDR of 37 F° and thus a nightly low of 104 – 37 = 67°F at design conditions (40/20°C, with MDR of 20.6C°). Enter the psychrometric analysis (Fig. 10.33) at the convenient and slightly more severe conditions of 105°F DB, 70 WB noted as point A (40.6 and 21.1°C). Note that RH = about 17% in this desert location.

Next, examine the earth tube conditions:

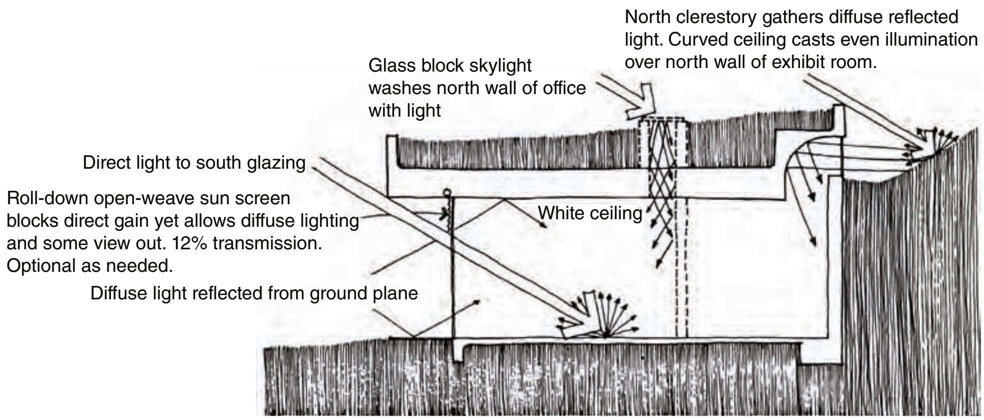
1. Determine t_{GW}: From Fig. 10.31, the deep-earth temperature is about 64°F (17.8°C).
2. Determine t_{AMP}: The seasonal amplitude (from Fig. 7.10) is about 19F° (10.6C°).
3. Determine CF: In dry (desert) soil, this amplitude extends to 14 ft (4.3 m).
4. Determine D: The given trench depth is 6 ft (1.8 m).

(*a*)

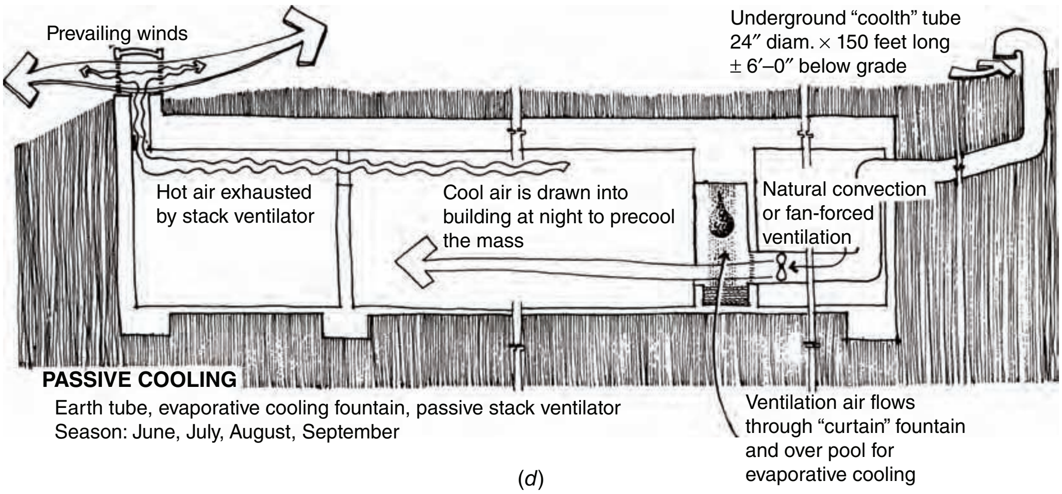


(*b*)

Fig. 10.32 *Visitor Center for the Antelope Valley California Poppy Reserve near Palmdale, California. (a) The Visitor Center is set into the field of poppies; an 8-kW wind generator and the earth tube intake can be seen on the hillside above. (b) Plan shows earth sheltering for an elongated east–west axis, served both by direct-gain and Trombe wall solar heating and by earth tube/evaporative cooling. (c) Solar energy enters mostly through the south glass; the glass-block skylights and north clerestory are mostly for even distribution of daylighting. At rest rooms, a vented Trombe wall is used. Thermal shades on the interior protect the south glass and north clerestory on winter nights; a roll-down exterior sunscreen greatly reduces direct solar gain through south glass in summer. Concrete block walls and concrete roof and floor provide thermal mass, as useful for summer cooling as for winter solar heating. (d) In summer, the desert air first passes through an earth tube (assisted by a fan), then is evaporatively cooled within the building, in sight of visitors. This cooled air picks up the building's heat and is then exhausted from the stack ventilator. (Courtesy of The Colyer/Freeman Group, San Francisco.)*



(*c*)



(*d*)

Fig. 10.32 *(Continued)*

5. Determine t_{SG}: The late summer ground temperature around the earth tube:

$$t_{SG} = (t_{GW}) + (t_{AMP})\,[1 - (D/CF)]$$
$$= (64) + (19)\,[1 - (6/14)]$$
$$= (64) + (10.9) = \text{about } 75°F\ (23.9°C)\ \textit{at most}.$$

Note that during the April poppy season, the earth temperature is likely to be at the yearly average of 64°F (17.8°C).

The air in the earth tube will be about 4F° (2.2C°) above this late-summer temperature, or 74.9 + 4 = approximately 79°F (26.1°C). (This may not sound very cool, but compare it to 104°F [40°C] outside.) To follow what happens to the air in the tube, move horizontally on the chart in Fig. 10.33, from point A toward point *B* at 79°F DB (26.1°C): at 79°F DB and about 62°F WB, the RH in the air has risen to about 34%.

At this point, the air enters the building through a small fountain consisting of water droplets. To chart this evaporative cooling, move from point B along the constant 62°F (16.7°C) WB line. If this fountain is a really good heat exchanger, we might achieve 80% of the distance from point B to saturation; call that point C (about 66°F DB, 62°F WB [18.9°C DB, 16.7°C WB], RH now = 80%). This combination (of pessimistic air/earth temperatures and optimistic evaporative cooling expectations) is actually below the summer comfort zone!

The air now begins to pick up heat from the building's interior. With few sources of latent heat, we follow sensible heat gain horizontally to the

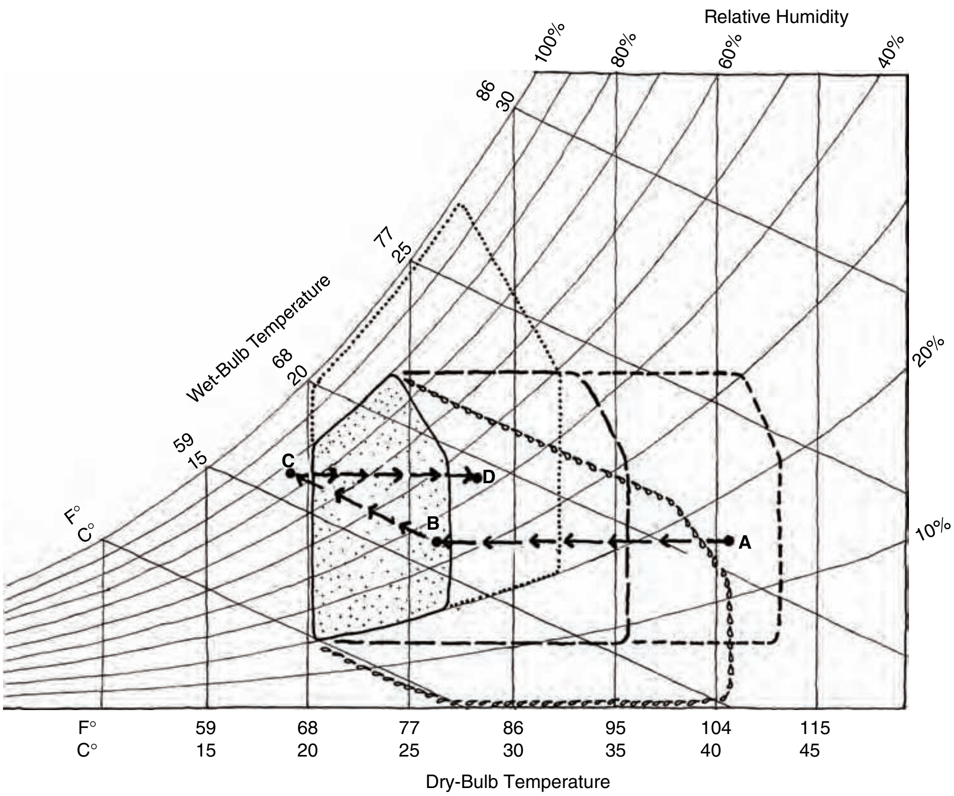


Fig. 10.33 *Following the path of passively cooled air at the Antelope Valley Visitor Center. Under summer design conditions, air enters the earth tube at point A. It is sensibly cooled within the tube, perhaps to the extent shown at point B. It then enters the building through a small fountain, perhaps being evaporatively cooled as far as point C. As the cooled air then picks up sensible heat from the building, the air heads toward point D, where it is exhausted through the stack ventilator.*

right; if we are to maintain an interior temperature of, say, 82°F (27.8°C)—with air motion and cool underground surfaces—the air can be heated to point D: 82°F DB, 67°F WB (27.8°C DB, 19.4°C WB), RH = about 47%. In this condition, it is discharged through the stack ventilator at the west end of the building. (Note that it is much cooler than the outdoor air at point A, even at the point of discharge.)

But does this theoretical process actually occur? We must complete the calculation process:

6. Determine the temperature difference that makes cooling possible. For the psychrometric equivalent process,

$$\Delta t = \text{outdoor temperature} - t_{SG}$$
$$= 105°\text{F} - 75°\text{F} = 30\text{F}° \ (40.6°\text{C} - 23.9°\text{C} = 16.7\text{C}°)$$

7. Determine the long-term cooling rate:

$$\text{Btu/h ft of tube length} = (\Delta t)\ (C)\ (\text{Area, tube surface, ft}^2\text{/ft of length});$$

Here, $C = 0.11$ for dry soil.

Btu/h ft of tube length

$$= (30\text{F}°)(0.11)\left[\frac{24 \text{ in.} \times \pi \times 1 \text{ ft length}}{12 \text{ in./ft}}\right]$$

$$= 20.7 \text{ Btu/h ft (equivalent to 19.9 W/m)}$$

Note that this rate is similar to that of the tubes in Table G.12, most of which are smaller in diameter but are located in moist soil. This tube will therefore cool outdoor air at the rate of (20.7 Btu/h ft) × (150 ft) = 3105 Btu/h under summer design conditions (19.9 W/m × 45.7 m = 910 W).

If the air in the tube is to drop from 105°F (40.6°C) to the 79°F (26.1°C) assumed at point B in Fig. 10.33, at what rate must it move?

$$\text{Btu/h} = \text{flow rate, cfm} \times 1.1 \times \Delta t$$
$$3105 = \text{cfm} \times 1.1 \times [105 - 79]$$
$$(\text{W} = \text{L/s} \times 1.2 \times \Delta t)$$

The flow rate, 3105/28.1 = 111 cfm (52.4 L/s), is substantially less than the flow rates typical of Table

G.12. Checking the velocity in this 2-ft. (0.6 m)-diameter tube,

$$\text{ft/min} = \text{cfm/ft}^2 \text{ of cross section}$$
$$\text{velocity, ft/min} = 111/\pi(1\text{-ft radius})^2$$
$$= \text{about } 35 \text{ ft/min } (0.18 \text{ m/s})$$

again substantially less than the velocities typical of Table G.12.

It is likely that much more outdoor air will be pulled through the tube, thus entering the building at a higher temperature. Then evaporative cooling through the fountain will be necessary to deliver air that is within the comfort zone.

For example, assume that for the cooling rate of 20.7 Btu/ft of length (based upon 105°F outside air, 75°F t_{SG}) and resulting total cooling of 3105 Btu/h, the fan provides a modest flow rate of 500 cfm. Then

$$3105 \text{ Btu/h} = 500 \text{ cfm} \times 1.1 \times \Delta t$$
$$(910 \text{ W} = 236 \text{ L/s} \times 1.2 \times \Delta t)$$
$$\Delta t = 5.65 \text{ F}° \ (\Delta t = 3.2\text{C}°)$$

The outdoor air then leaves the tube (new point B) at about 99°F DB, 68°F WB (37.2°C DB, 20°C WB) and, with successful exposure to evaporative cooling in the fountain, might reach (new point C) 75°F DB, 68°F WB (23.9°C DB, 20°C WB), quite humid but within the comfort zone and likely welcome in this desert environment. It then could absorb some heat from the building before it is exhausted. ■

References and Resources

Abrams, D. W. 1986. *Low Energy Cooling*. Van Nostrand Reinhold. New York.

ASHRAE. 2007. ANSI/ASHRAE/IESNA Standard 90.2-2007, *Energy-Efficient Design of Low-Rise Residential Buildings.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2013. *ASHRAE Handbook—Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 1997. *ASHRAE Handbook—Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Balcomb, J. D., D. Barley, R. McFarland, J. Perry, Jr., and W. Wray. 1980. *Passive Solar Design Handbook,* Vol. 2, *Passive Solar Design Analysis*. U.S. Department of Energy. Washington, DC.

Balcomb, J. D., R. Jones (ed.), R. McFarland, and W. Wray. 1984. *Passive Solar Heating Analysis.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Berry, B., J. Bown, J. Thornton, J. Turzynski, and M. Walton. 1995. "The New Inland Revenue Centre, Nottingham." *The Arup Journal*, April. Ove Arup Partnership, London.

Bowen, A., E. Clark, and K. Labs. 1981. *Passive Cooling*. American Solar Energy Society. Boulder, CO.

Brown, G. Z. and M. DeKay. 2000. *Sun, Wind & Light*, 2nd ed. John Wiley & Sons. New York.

Chandra, S., P. W. Fairey, and M. Houston. 1986. *Cooling with Ventilation*. Solar Energy Research Institute. Golden, CO.

Fleischhacker, P., D. Bentley, and G. Clark. 1982. "A Simple Verified Methodology for Thermal Design of Roof Pond Cooled Buildings," in *Proceedings of the 7th National Passive Solar Conference.* American Solar Energy Society. Boulder, CO.

Gardner, I. and D. Hadden. 1992. "UK Pavilion, Expo '92, Seville." *The Arup Journal*, Autumn. Ove Arup Partnership. London.

Givoni, B. 1994. *Passive and Low Energy Cooling of Buildings*. Van Nostrand Reinhold. New York.

Johnson, T. 1981. *Solar Architecture: The Direct Gain Approach*. McGraw-Hill. New York.

Mazria, E. 1979. *The Passive Solar Energy Book*. Rodale Press. Emmaus, PA.

Miller, H. (ed.). 1980. *Passive Cooling Handbook: Proceedings of the Passive Cooling Workshop held in conjunction with the Fifth National Passive Solar Conference.* American Solar Energy Society. Boulder, CO.

Milne, M. and B. Givoni, 1979. "Architectural Design Based on Climate," in *Energy Conservation Through Building Design*, D. Watson (ed.). McGraw-Hill, New York.

Niles, P. and K. Haggard. 1980. *California Passive Solar Handbook*. California Energy Commission. Sacramento, CA.

Olgyay, V. 1963. *Design with Climate: Bioclimatic Approach to Architectural Regionalism.* Princeton University Press. Princeton, NJ.

SERI. 1981. *A New Prosperity: The SERI Solar Conservation Study*. Brick House Publishing. Andover, MA.

Stromberg, R. P. and S. O. Woodall. 1977. *Passive Solar Buildings: A Compilation of Data and Results*, SAND-77-1204. Sandia Labs. Albuquerque, NM.

Thompson, T., N. Chalfoun, and M. Yoklic. 1994. "Estimating the Performance of Natural Draft Evaporative Coolers." *Energy Conversion Management*, Vol. 35, No. 11. Elsevier Science Ltd. London, UK.

U.S. Department of Energy. *Building Energy Software Tools Directory*. http://www.eere.energy.gov/buildings/tools_directory/

Utzinger, M. and J. H. Wasley. *Building Balance Point*. Vital Signs Curriculum Project Resource Module. Scroll and click: http://arch.ced.berkeley.edu/vitalsigns/res/rps.html

Watson, D. and K. Labs. 1983. *Climatic Design: Energy-Efficient Building Principles and Practices*. McGraw-Hill. New York, NY.

Wittwer, V., W. Platzer, and M. Rommell. 1991. "Transparent Insulation." *Solar Today*, January–February, 1991.

Yoklic, M. and M. Layseca. 1998. "Earth Construction, Courtyards, Verandahs, and Cooltowers: An Arizona Ranch House with Middle East Vernacular," in *Proceedings of the 23rd National Passive Solar Conference.* American Solar Energy Society. Boulder, CO.

C H A P T E R 11

Integrating Passive Systems

CHAPTERS 1 THROUGH 10 PROVIDE SOME PREPARATION for design: a perspective on energy, water, and material resources; an understanding of human comfort and indoor air quality; an analysis of the climate resources available on site; a list of the general design strategies appropriate to various climates; a discussion of the basics of heat transfer calculations; components of the building envelope; daylighting design; and passive heating and passive cooling guidelines. Hence, we now know much about the variables outside of a building, the desired conditions inside, and the individual components of a building's skin. In this chapter, all these variables are integrated into the process of designing for passive heating and cooling with the important related factor of daylighting.

This chapter is intended as a demonstration of the decision-making design process for the passive performance of a small office building. The project takes the user through the steps and calculations of the principles and concepts described in the previous chapters—serving as an example (with guidance) for any project at the schematic planning stages of design.

The decision-making process for this example is outlined in Table 11.1. This table shows which chapters, guidelines, and strategies to use for buildings that use renewable energy versus buildings that use imported energy.

TABLE 11.1 Decision-Making Process for Integrating Passive Systems

<table>
<tr><th>Buildings Using On-Site Energy</th><th>Buildings Using Imported Energy</th></tr>
<tr><td colspan="2">Prior Decisions: Chapter 3. Sites and Resources
Chapter 4. Thermal Comfort
Chapter 7. Heat Flow
Chapter 8. Daylighting</td></tr>
<tr><td>Section 9.3 Guidelines: Passive Heating</td><td></td></tr>
<tr><td colspan="2">← Section 9.4 Calculating Worst-Hourly Heat Loss →</td></tr>
<tr><td></td><td>Section 9.5 Calculations for Heating-Season Fuel Consumption (imported energy)</td></tr>
<tr><td>Section 9.6 Detailed Calculations: Passive Heating Performance</td><td></td></tr>
<tr><td>Section 10.3 Summer Heat Gain Guidelines</td><td></td></tr>
<tr><td>Section 10.4 Passive Cooling Guidelines</td><td></td></tr>
<tr><td>Section 10.5 Reintegrating Daylighting, Passive Solar Heating, and Cooling</td><td></td></tr>
<tr><td colspan="2">← Section 10.6 Approximate Method for Calculating Heat Gain (Cooling Load) →</td></tr>
<tr><td></td><td>Section 10.7 Detailed Hourly Heat Gain (Cooling Load) Calculations</td></tr>
<tr><td>Section 10.8 Detailed Calculations: Passive Cooling Performance</td><td></td></tr>
</table>

11.1 ORGANIZING THE DESIGN PROBLEM

Renewable sources of on-site energy for lighting, heating, and cooling allow a building to function with less need for imported energy sources. As building designs are shaped by the use of on-site sources, they become more regional in appearance. This works against the one-design-fits-all approach common to chain retailing (such as fast-food outlets or electronics specialty stores), but works for the subtle integration of a building into its regional climate and culture, while reducing the economic and environmental costs of imported energy.

How should the building envelope respond to the sometimes conflicting needs for heating, cooling, and daylighting? Heating and cooling design strategies were related to comfort and climate in Chapter 10, where it became evident that internal heat gains can shift the appropriate design strategies for a building toward cooling, perhaps eliminating heating needs entirely. Typically, much of this internal heat is provided by electric lighting. Daylighting can replace electric lighting for most of the typical working day in most building types—*if* the building is designed to allow daylight to reach most of the interior.

In summer, properly shaded daylighting openings contribute less heat gain than the electric lighting that the daylight is replacing. This reduces the need for both electricity and cooling. In winter, some solar gain through daylight openings assists with heating (especially with south-facing windows), but the daylight still replaces electric lighting that would otherwise be an additional source of heat. Thus, compared to a conventional building of the same size and function, the daylit building is likely to use more heating energy (unless passive solar heating is emphasized), less electricity for lighting, and less cooling energy.

A matrix of design strategies (Fig. 11.1) covered in Chapter 8 (daylighting), Chapter 9 (passive heating), and Chapter 10 (passive cooling) illustrates some opportunities for a simple one-space building across a range of on-site energy sources. *Ventilative* cooling strategies depend upon the air as a heat sink; *evaporative/radiative* cooling strategies depend upon both sky and air as heat sinks; *earth coupling* cooling strategies depend upon the earth as a heat sink.

11.2 EXAMPLE DESIGN PROJECT

The following example will illustrate how to apply daylighting, passive heating, and passive cooling guidelines to the Emerald People's Utility District (EPUD) office building (Fig. 11.2), located near Eugene, Oregon. This 24,000-ft^2 (2230-m^2) building is located in western Oregon's wet-winter, dry-summer climate, typical of the U.S. Pacific Northwest. Energy conservation and daylighting considerations were major goals in this building's design and were integrated with solar heating, night ventilation of mass, structure, and acoustics.

EXAMPLE 11.1 This sample problem is an ongoing illustration. Applications of various design guidelines appear in the context of this example throughout this chapter. Table 11.2 presents the type of information about a building that will be required in order to apply these design guidelines.

- Part A. Daylighting Design
- Part B. Overall Heat Loss
- Part C. Approximate Solar Savings Fraction (SSF)
- Part D. Approximate Heat Gain
- Part E. Cross-Ventilation Guidelines
- Part F. Night Ventilation of Thermal Mass Guidelines
- Part G. January Balance Point Temperature
- Part H. Annual SSF Based upon the Load Collector Ratio (LCR)
- Part I. Clear January Day Indoor Temperature Swing
- Part J. Detailed Night-Cooling of Mass Calculation ■

EXAMPLE 11.1, PART A Daylighting Design Daylighting design for this office building began with design diagrams (Fig. 11.3) and an assessment of daylighting potential (Fig. 11.4). After it was established that daylighting was available during almost all normal working hours, the building plan was organized so that almost all windows faced either south or north to avoid the problems of low-altitude sun (year-round glare and summer heat gain) that accompany east- and west-facing windows. Then the building section was designed so that the height of the windows (H) was related to the depth of the floor plan served by those windows (2.5H).

After a generous target DF_{av} = 4.0% was chosen from Table 8.3, the next step was to size the windows and clerestories (as skylights), using the DF guidelines from Table 8.6. Applicable formulas for both sidelighting and for vertical monitor skylights:

$$DF_{av} = 0.2\ \frac{\text{window (or skylight) area}}{\text{floor area}}$$

Applied to the entire typical bay,

$$DF_{av} = 0.2\ \frac{97\ \text{ft}^2\ \text{north} + 97\ \text{ft}^2\ \text{south} + 132\ \text{ft}^2\ \text{clerestory}}{1440\ \text{ft}^2}$$

= 0.45, or 4.5%

slightly above the target DF_{av} of 4.0%.

Note that in this example, DF_{min} from the sidelighting occurs near the center of the building, at about the point (on the second floor) where the most light is available from the skylight. Therefore, relatively even daylighting distribution is expected on the upper floor. This is helped by the use of lightshelves and the T-shaped windows shown in Fig. 11.2*g* and *h*.

The seasonal window-size question (more needed in winter, less in summer) was answered in this example by the use of deciduous vines outside the south windows. In winter and cool spring, the vines are bare of leaves. Warm weather brings leafy shade lasting well into the warm fall (Fig. 11.2*i* and *j*). ■

The target daylight factors listed in Table 8.3 provide sufficient light during most of the daylight hours on overcast winter days. The relationship between office working hours, daylight, and outdoor temperature is explored in the *climatic timetables* of Fig. 11.4. Much more light will be available on summer days—probably more light than is needed, bringing heat along with it. When sizing windows and skylights, remember that controlling direct sun is necessary and that less opening area is needed in summer than in winter.

EXAMPLE 11.1, PART B Overall Heat Loss Find the overall rate of heat loss, in Btu/DD ft^2.

SOLUTION

This office building is passively solar heated, so the overall rate of heat loss, in Btu/DD ft^2, is determined by using the total $U \times A$ of the non-south-glass envelope. From Table 11.2, this is 42 + 25 + 72 = 139 Btu/h °F.

To this must be added the effects of ventilation. From the same table, outdoor air is shown to be supplied at the rate of

$$20\ \text{cfm/person} \times 8\ \text{persons} = 160\ \text{cfm}$$

which can also be expressed as 160 cfm × 60 min/h = 9600 cfh. Comparing this hourly rate to the volume of the typical bay, we have:

$$\frac{9600\ \text{ft}^3/\text{h}}{22{,}000\ \text{ft}^3} = 0.44\ \text{ACH}$$

The $U \times A$ for ventilation is therefore

$$0.44\ \text{ACH} \times 22{,}000\ \text{ft}^3 \times 0.018 = 174\ \text{Btu/h °F}$$

and the total rate of heat loss is

$$\frac{(139\ \text{Btu/h °F} + 174\ \text{Btu/h °F}) \times 24\ \text{h/day}}{1440\ \text{ft}^2} = 5.2\ \text{Btu/DD ft}^2$$

The Eugene, Oregon, climate corresponds most closely to the location of Salem, Oregon, as listed in Table C.19, where we find DD65 in Salem = 4852 per year. From Table 9.1, the maximum recommended rate of heat loss for a passively solar-heated building in a 3000- to 5000-DD climate is 5.6 Btu/DD ft^2. This building's heat loss rate is under this maximum, suggesting enhanced energy conservation. ■

EXAMPLE 11.1, PART C Approximate Solar Savings Fraction (SSF) Find the approximate SSF of a typical bay.

SOLUTION

Standard-performance windows (simple double-glazed) are used in this building, and the approximate SSF can be found from Table 11.2 (building data) and Table G.1 (SSF guidelines) as follows:

$$\frac{\text{south glass area } 97\ \text{ft}^2 + 132\ \text{ft}^2}{\text{floor area } 1440\ \text{ft}^2} = 0.16$$

For Salem, Oregon, with standard-performance windows, a range of 0.12 to 0.24 for glass/floor

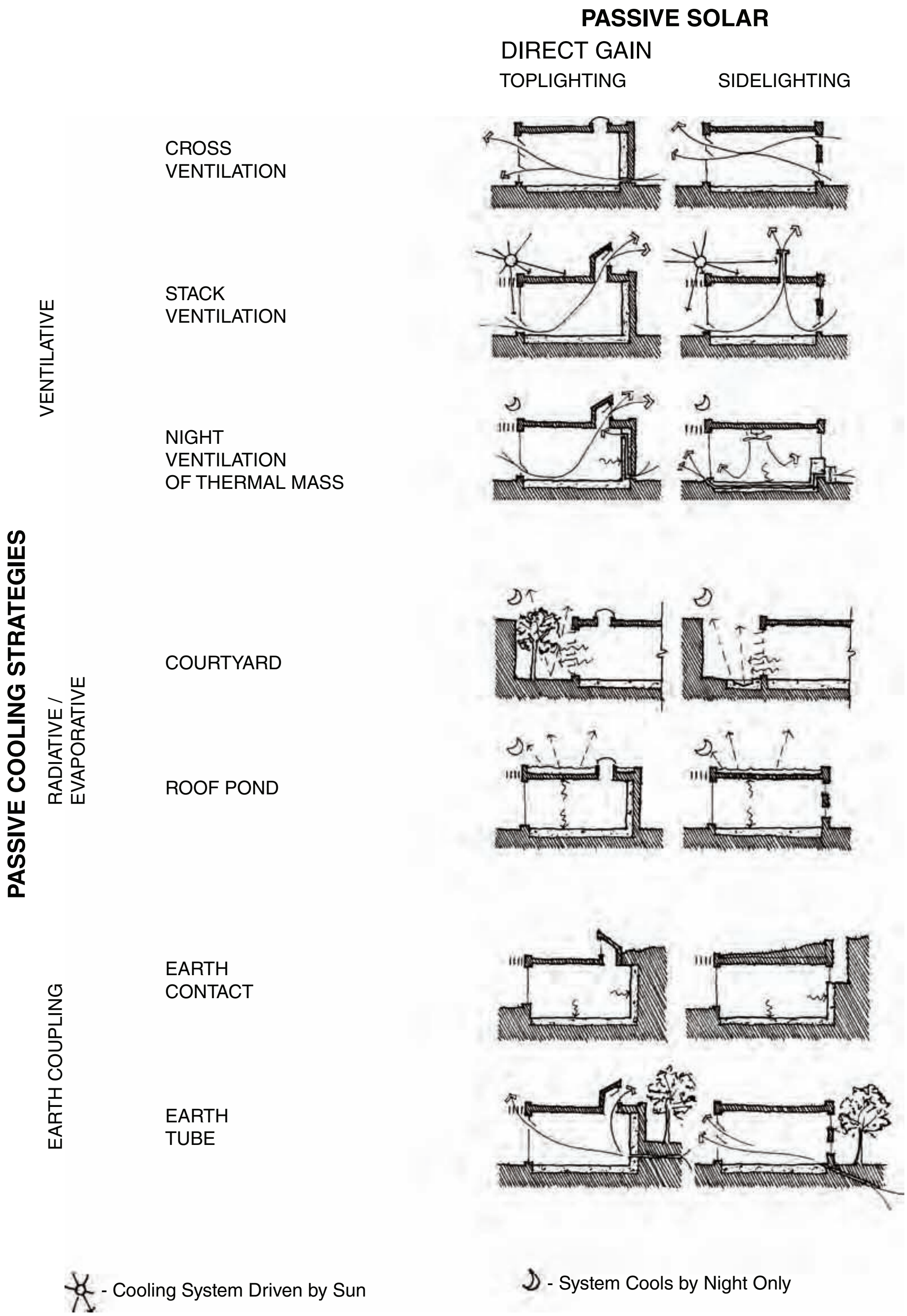


Fig. 11.1 *Combining daylight, passive cooling, and passive solar heating opportunities. These schematic sections of simple one-room buildings remind designers of the potential for site-based, renewable resources and how they might interact. (Sharon Shoshani and Alan Rutherford, University of Oregon class project.)*

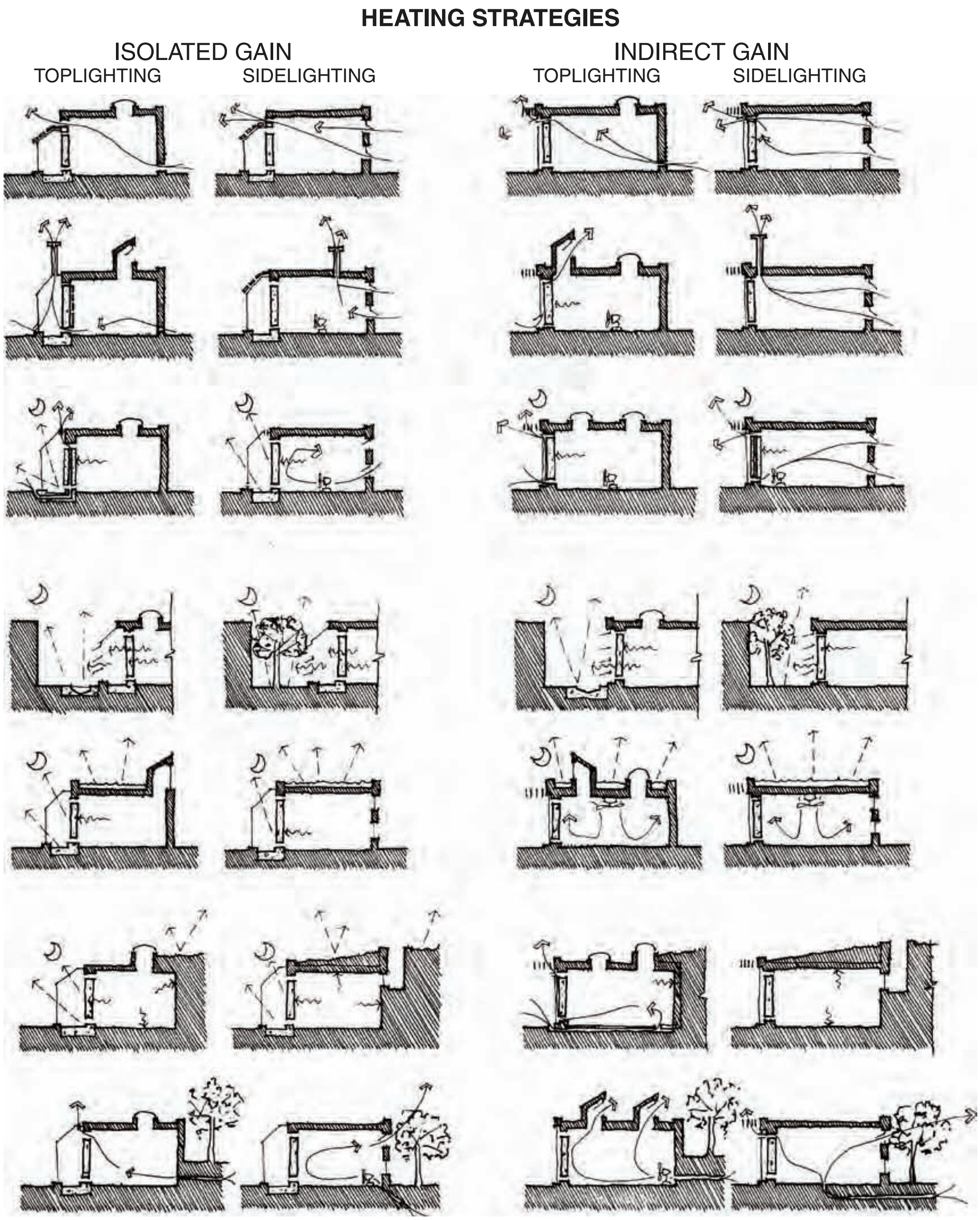
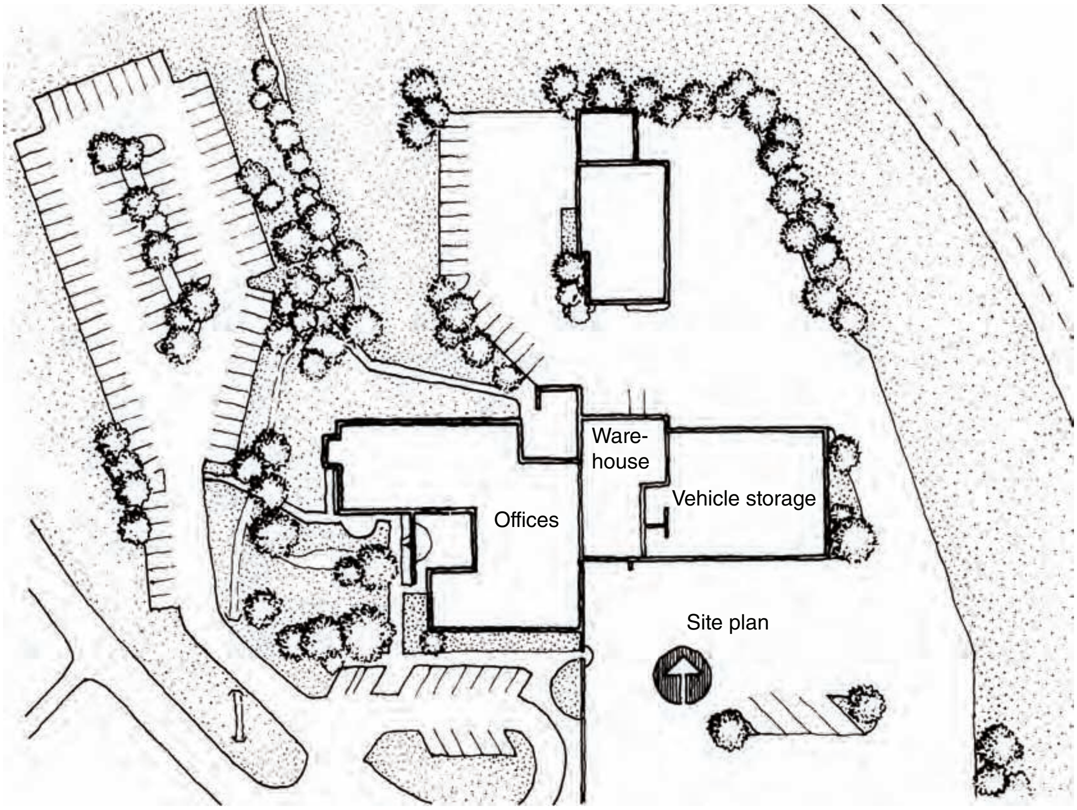


Fig. 11.1 (Continued)



(*a*)

Fig. 11.2 *The office building for the Emerald People's Utility District (EPUD) near Eugene, Oregon, is elongated east–west for maximum window areas facing north–south. (a) The site plan, (b) the ground-floor plan, (c) the second-floor plan, and (d) a section through a two-story wing. The cutaway axonometric (e) of a typical open-office two-story bay shows air flush through hollow cores of exposed precast concrete slabs, windows and shading, and suspended sound-absorbing baffles. The deciduous vines on trellises at the south façade change the building's appearance by season. (f) Diagrammatic daylighting section of the office building for the Emerald People's Utility District near Eugene, Oregon. Lightshelves (g) reduce the contrast between a lot of daylight near windows and too little daylight farther in. The resulting windows (on north façade) are T-shaped (h), with more glass area above the lightshelves and less glass below. (i) At the summer solstice, the shading stripes will soften as vines leaf out with age; at the fall equinox, the leaves will still shade, whereas at the spring equinox (j) the branches will be bare to allow sun to reach the windows; (k) at the winter solstice, most of the window is exposed to the sun. (Drawing* c *is courtesy of Virginia Cartwright. Courtesy of Equinox Design, Inc., and WEGroup, PC, Architects, Eugene, OR.)*

ratio yields SSF 21 to 32%. So, with an actual ratio of 0.16, the approximate SSF is determined as follows:

Salem ratio range 0.24 – 0.12 = Δ0.12
Salem SSF range 32% – 21% = Δ11%
(Actual ratio 0.16)
– (Salem minimum ratio 0.12) = 0.04,

$$\text{therefore} = \frac{0.04\ (\Delta 11\%)}{\Delta 0.12}$$

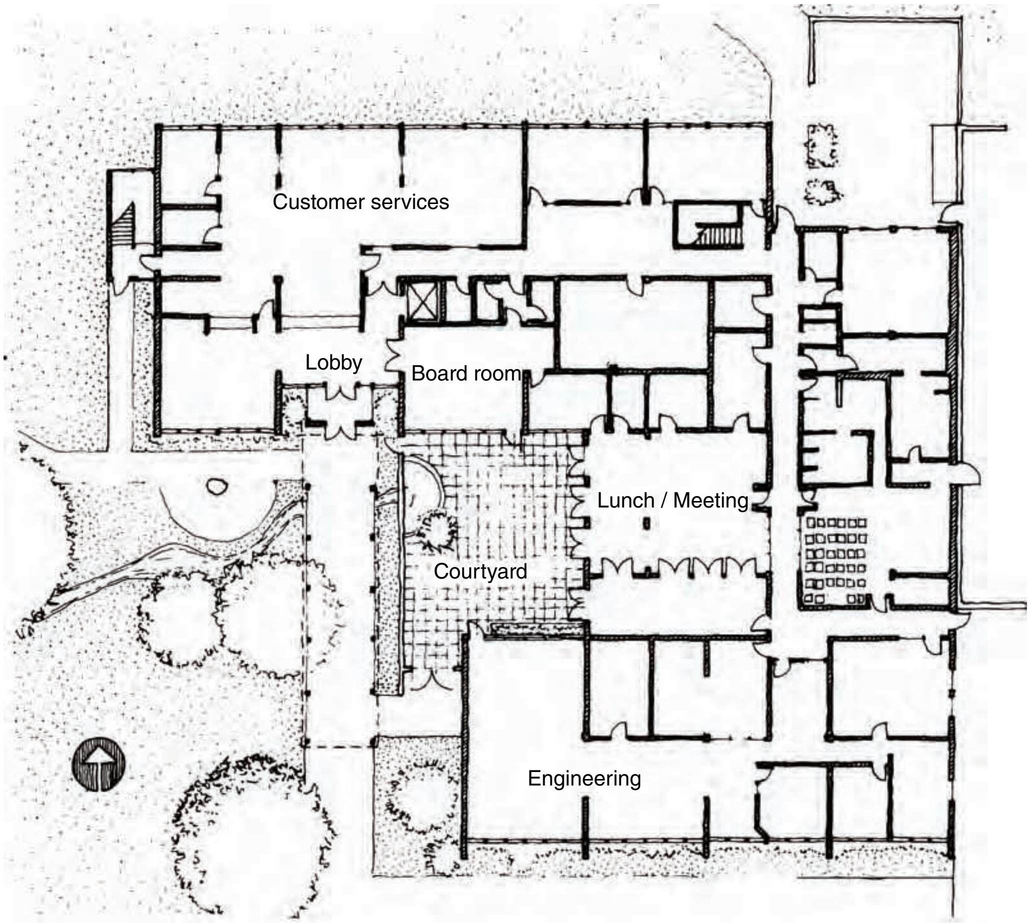
$$= 3.7\%, \text{ to be added to the minimum SSF;}$$

$$\text{Actual SSF} = \text{minimum } 21\% + 3.7\% = 24.7\%$$

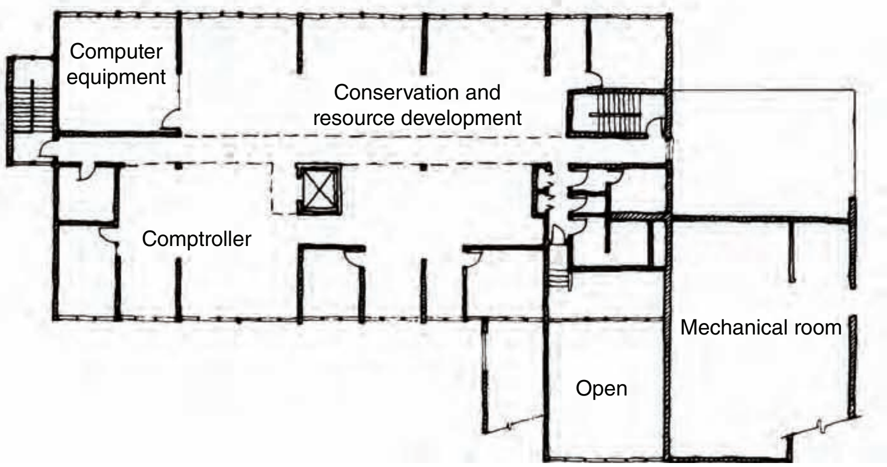
This glass area/floor area ratio (0.16) is consistent with the previously calculated daylighting design considerations, although there is somewhat more south wall area that could be utilized for additional solar heat collection. (If more solar heat but not more daylight is desired, the additional collection area could be provided as a Trombe wall.)

Table G.2 shows that direct-gain thermal mass appropriate to SSF = 25% would be about 75 lb of masonry per square foot of south glass, or about 2 ft^2 of mass surface per square foot of south glass. From Table 11.2, the total exposed area of thermal mass in this typical bay is 2232 ft^2:

2232 ft^2 mass/229 ft^2 south glass
= almost 10 ft^2 mass/ft^2 glass

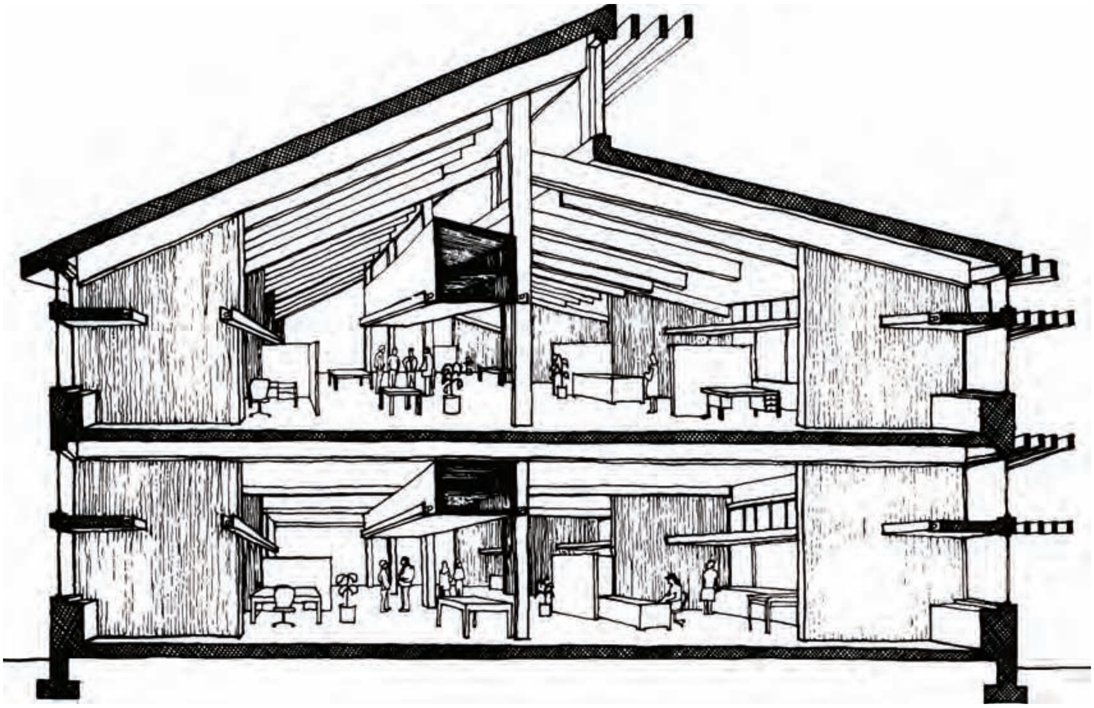


(*b*)



(*c*)

Fig. 11.2 *(Continued)*



(*d*)

Fig. 11.2 *(Continued)*

This is much more mass area than the minimum recommended. This excess of mass area will help prevent overheating on sunny winter days and contribute to thermal stability year-round. For a more detailed analysis of this building's SSF, see Example 11.1, Part H.

At this point, one must wonder why standard- rather than superior-performance windows were used. For Salem, the approximate SSF would have increased to about 44%, with more than adequate internal areas of thermal mass. The simple answer is that the client did not want movable insulation, and superwindows were not available at an attractive cost when the building was being designed. ■

EXAMPLE 11.1, PART D Approximate Heat Gain
Find the approximate heat gains from people, lighting, envelope, and ventilation.

SOLUTION
Look up values in Table G.3:

A. People and equipment (using the high end for Europe office buildings, based on assumptions about computer use) 5.8 Btu/h ft²
B. Electric lighting (with a 4% DF from Example 11.1, Part A; this procedure assumes that most electric lighting is off when daylight is available) 0.5 Btu/h ft²
C. Envelope (Eugene's design temperature, from Table B.5, is 89°F)

South glass, shaded by vines:

$$\frac{(97\ \text{ft}^2 + 132\ \text{ft}^2) \times 16}{1440\ \text{ft}^2} \qquad 2.54\ \text{Btu/h ft}^2$$

North glass, unshaded (Table G.6 Part B; regular double glass, venetian blinds):

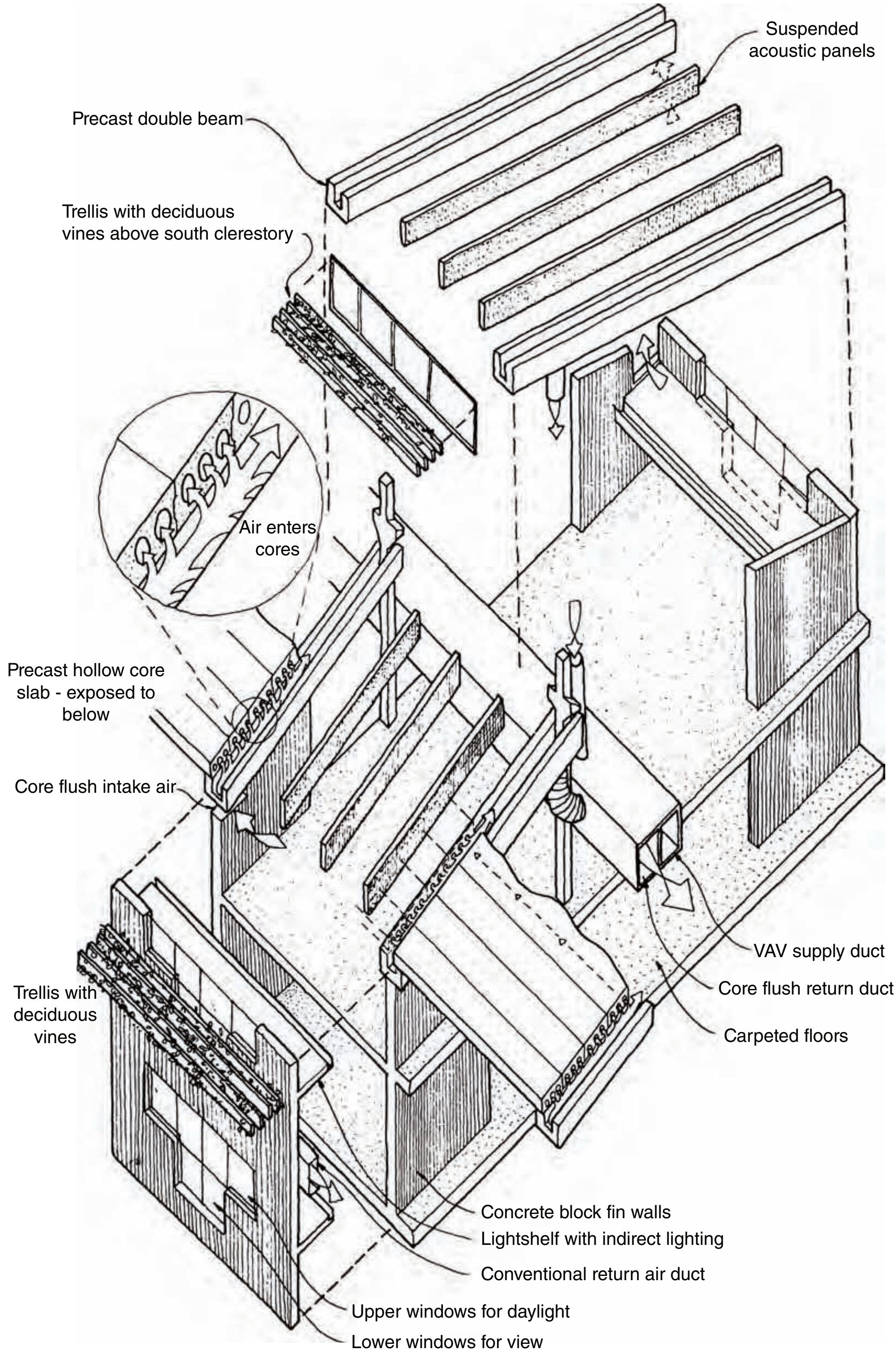
$$\frac{97\ \text{ft}^2 \times 14\ \text{Btu/h ft}^2}{1440\ \text{ft}^2} \qquad 0.94\ \text{Btu/h ft}^2$$

Walls:

$$\frac{296\ \text{ft}^2 \times 0.084\ \text{Btu/h ft}^2\ °\text{F} \times 15}{1440\ \text{ft}^2} \qquad 0.26\ \text{Btu/h ft}^2$$

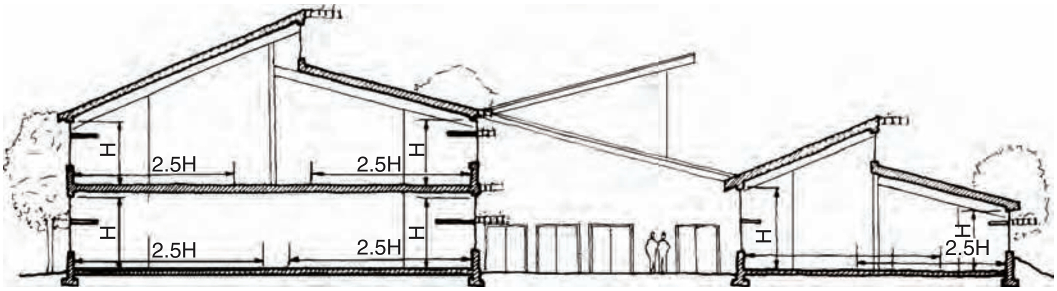
Roof:

$$\frac{1512\ \text{ft}^2 \times 0.028\ \text{Btu/h ft}^2\ °\text{F} \times 35}{1440\ \text{ft}^2} \qquad 1.03\ \text{Btu/h ft}^2$$

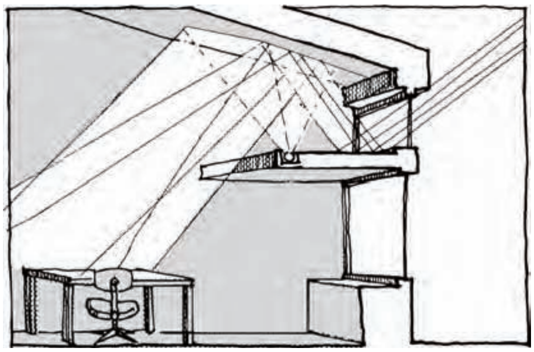


(*e*)

Fig. 11.2 *(Continued)*



(*f*) Daylighting cross section (south to right)



(*g*) Lightshelves

(*h*) North façade

Fig. 11.2 *(Continued)*

(*i*) South façade: summer solstice

(*j*) South façade: spring equinox

(*k*) South façade: winter solstice

Fig. 11.2 *(Continued)*

TABLE 11.2 Design Data for a Typical Second-Floor Bay of the Office Building (Fig. 11.2*e*)

Component of Envelope	U-Factor (Btu/h ft² °F)	Area (ft²)	U × A (Btu/h °F)
Floor Area (basis for guidelines)		1440	
Exposed to Outside			
Roof[a]	0.028	1512	42
Exterior opaque walls[b] (north and south)	0.084	296	25
North window[c]	0.74	97	72
Total for passive solar guidelines[d] UA_{ns}			139
South window[c]	0.74	97	
South clerestory[c]	0.74	132	
Total for passive solar guidelines A_p		229	
Interior Thermal Mass			
Roof underside		1512	
Bearing walls, beams and columns		720	
Total for passive heating and cooling		2232	
Ventilation			
Volume of enclosed space, 22,900 ft³			
Occupancy is eight persons			
Ventilation is provided at the rate of 20 cfm per person			
Openable window area: 16 ft² on north, 16 ft² on south			

[a]R-40 over precast slab. Assume corrected R-35; therefore, U = 0.28.

[b]A 4-in. concrete block outside, 1-in. airspace, R-19 batt with metal studs at 24 in. and gypsum inside; approximate corrected R-11.9; therefore, U = 0.084.

[c]Clear double-glazed, 3/8-in. airspace, nonthermal break aluminum, U = 0.74.

[d]Passive solar heating calculations do not directly include losses from south-facing glass. Also, there is no floor heat loss or gain, because this is a second-floor space.

D. Total heat gains, internal and through building skin:

11.07 Btu/h ft²

E. Heat gains from ventilation:

$$\frac{20 \text{ cfm/person} \times 8 \text{ persons} \times 16}{1440 \text{ ft}^2} \qquad 1.8 \text{ Btu/h ft}^2$$

Total approximate heat gains: 12.87 Btu/h ft² ■

EXAMPLE 11.1, PART E Cross-Ventilation Guidelines Find the required inlet areas for cross-ventilation of a typical bay.

SOLUTION

The monthly average wind velocities for Eugene, Oregon, may be obtained from NOAA Local Climatological Data. For July, the hottest month, the average wind velocity is about 8 mph (typically from a nearly due-north direction). From Table 11.2, the inlet area (equal to outlet area also in this case) is 16 ft². The inlet area, as a percentage of floor area, is therefore

$$16 \text{ ft}^2/1440 \text{ ft}^2 = 1\%$$

Entering Fig. 10.5 with 8-mph wind velocity and 1% inlet area, we find that somewhat less than 15 Btu/h ft² heat gain can be removed by cross-ventilation. In Example 11.1, Part D, we approximated a heat gain (excluding ventilation) of about 11 Btu/h ft². Therefore, under average July conditions, the window area is probably adequate to remove heat gains and maintain an indoor temperature 3F° *above* the outdoor temperature.

Eugene's average July daily high is 83°F. This would produce an interior daily high of 86°F. Such a temperature would require somewhat more than minimum air motion in order for occupants to feel comfortable. At Eugene's summer *design* temperature of 89°F, the interior temperature would be 92°F. For these reasons this building was designed to be night ventilated, relying on thermal mass rather than on cross-ventilation for hot-day comfort.

In milder weather, these windows can achieve substantial cooling because the temperature difference, Δt, is more than the 3F deg assumed in Fig. 10.5. For example, when the temperature indoors is 75°F, outdoors 65°F, the fully opened windows with the 8-mph wind would result in a cooling rate of

$$\frac{\text{about 15 Btu/h ft}^2 \times 10 \text{ F deg}}{3 \text{ F deg}} = \text{about 50 Btu/h ft}^2$$

which is considerably more than the actual gain of 11 Btu/h ft². Therefore, under such conditions, the windows are only partially opened. ■

EXAMPLE 11.1, PART F Night Ventilation of Thermal Mass Guidelines Find the potential for night ventilation of mass.

SOLUTION

For Eugene, Oregon, from Table B.5, the summer design temperature is 89°F and the MDR is 31F°. From Table 11.2, the typical bay has a ratio of exposed thermal mass/floor area of

$$\frac{1512 \text{ ft}^2 + 720 \text{ ft}^2}{1440 \text{ ft}^2} = 1.55$$

which places this example halfway between average mass (ratio 1.0) and high mass (ratio 2.0). Entering Fig. 10.8*a*, with Eugene's climate data, we find that an average-mass building can store about 100 Btu/ft² day, whereas a high-mass building (Fig. 10.8*b*) can store about 170 Btu/ft² day. This building can therefore store about 135 Btu/ft² day.

Assuming a 9-hour typical working day (including the noon hour), at the average approximate heat gain rate of 13 Btu/h ft² (Example 11.1, Part D), the daily heat gain in this building is 9 h × 13 Btu/h ft² = 117 Btu/ft² day. This average heat gain is less than the storage capacity of 135 Btu/ft² day, so the building should perform satisfactorily with this method of cooling.

Although this building was designed for nighttime forced ventilation because of summer night calm, we will check to see whether the operable windows are adequate for natural night cross-ventilation. In Fig. 10.8*c*, we find that during the hour of maximum night cooling, somewhat less than 14% of the total stored heat gains must be removed:

$$14\% \times 117 \text{ Btu/ft}^2 \text{ day} = 16 \text{ Btu/h ft}^2$$

From Fig. 10.8*d*, the resulting maximum hourly Δt is about 13F°.

In Example 11.1, Part E, we determined that less than 15 Btu/h ft² would be removed by cross-ventilation under average July conditions at a 3F° Δt. Because during this hour of maximum cooling the indoor–outdoor Δt is 13F°, cross-ventilation could remove

$$\frac{13 \text{ F°} \times 15 \text{ Btu/h ft}^2}{3 \text{ F°}} = 65 \text{ Btu/h ft}^2$$

Cross-ventilation by night appears feasible for this building, because excess stored heat could be removed during this hour of maximum cooling. Unfortunately, Eugene's summer nighttime average wind velocity is nearly zero. Forced ventilation was therefore chosen. This also allows a thorough flushing of all interior mass surfaces with cool air.

The rate of forced ventilation during the hour of maximum cooling can be estimated from

$$V = \frac{q_v \times 60 \text{ min/h}}{(1.1 \text{ Btu min/ft}^3 \text{ F° h})(\Delta t)}$$

Expressed per square foot floor area in this building,

$$16 \text{ Btu/h ft}^2 = (V \text{ cfh})\ (0.018 \text{ Btu min/ft}^3 \text{ °F h})\ (13\text{F°})$$

$$V = \frac{16}{0.018 \times 13}$$

$$= 68.4 \text{ cfh outdoor air/ft}^2 \text{ floor area}$$

This rate of forced outdoor air ventilation produces the following air change with average ceiling height at 15.3 ft:

$$\frac{68.4 \text{ cfh/ft}^2 \text{ floor}}{15.3 \text{ ft}^3/\text{ft}^2, \text{ for 1 AC}} = 4.47 \text{ ACH}$$

a rate considerably greater than that required for minimum outdoor air per person by day. This promises an attractive indoor air quality by the next morning. ■

EXAMPLE 11.1, PART G January Balance Point Temperature Calculate the January balance point temperature for a typical bay. Assume that the average indoor January temperature over a 24-hour period is an energy-conserving 68°F.

SOLUTION

The (summer) internal gains from Example 11.1, Part D, may need some modifications. In darker winter, assume that the gain from electric lighting is closer to the 2 < DF < 4 value of 2.0 Btu/h ft². The internal gain is then 5.8 + 2.0 = 7.8 Btu/h ft² from people, equipment, and electric lighting. The average internal gains are as follows:

$$\frac{7.8 \text{ Btu/h ft}^2 \times 9 \text{ h}}{24 \text{ h}} = 2.93 \text{ Btu/h ft}^2$$

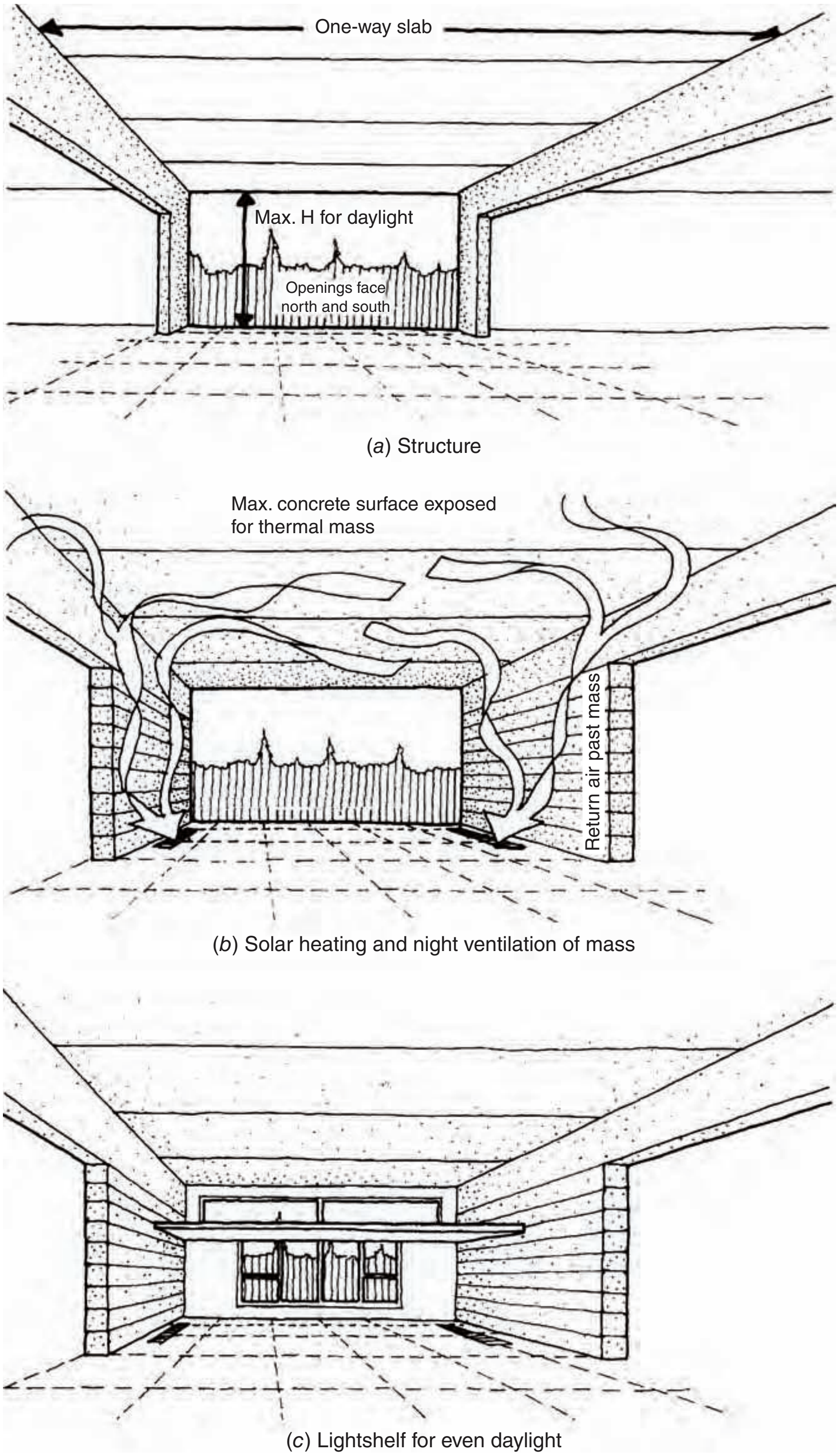
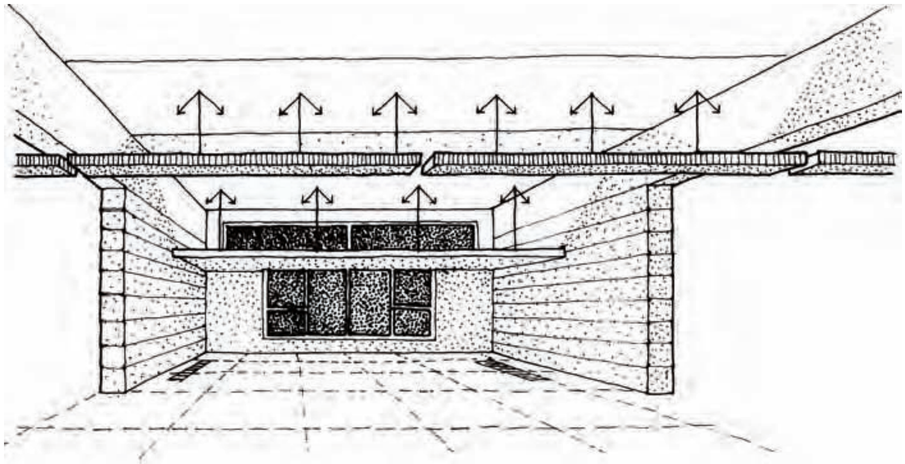
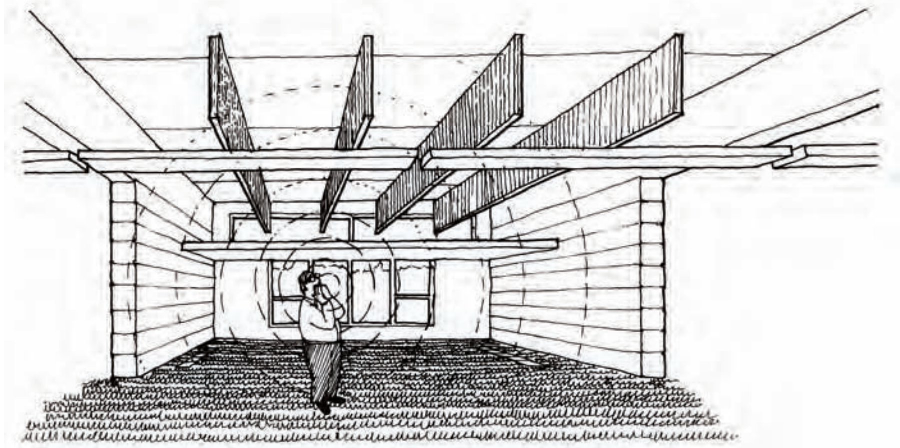


Fig. 11.3 *Design diagrams explore opportunities in the EPUD building. (a) Choosing a one-way structure allows windows to be placed as high as possible for deeper daylight penetration. (b) Maximizing exposed interior surfaces that are thermally massive facilitates both winter solar heat storage and summer night cooling. Carpet was installed at the insistence of the client. (c) Shaping the window with additional area above a lightshelf helps reduce the visual contrast near the window. (d) Indirect electric lighting is facilitated when higher ceilings are available; less glare on computer screens results. (e) With so much exposed mass surface, sound absorption is a must. This solution continues to expose the concrete ceiling and does not cast shadows from incoming daylight. (Drawings by Michael Cockram; © 1998 by John S. Reynolds, A.I.A.; all rights reserved.)*



(*d*) Indirect electric lighting



(*e*) Sound absorption

Fig. 11.3 *(Continued)*

The January solar gain, VS, from Table C.19, for Salem, Oregon, is 471 Btu/ft^2 day per ft^2 of south glass:

$$\frac{471 \text{ Btu/h ft}^2 \times (97 \text{ ft}^2 + 132 \text{ ft}^2) \text{ south glass}}{24 \text{ h} \times 1440 \text{ ft}^2}$$

$$= 3.1 \text{ Btu/h ft}^2$$

Therefore,

$$Q_i = 2.93 + 3.1 = 6.03 \text{ Btu/h ft}^2$$

UA for the typical bay (from Table 11.2 and Example 11.1, Part B) includes, for this calculation, all elements of the building envelope:

$$(42 + 25 + 72 + 72 + 98 + 174 \text{ infiltration})$$
$$= 483 \text{ Btu/h °F}$$

expressed per square foot of floor area:

$$483/1440 = 0.34 \text{ Btu/h °F ft}^2$$

Therefore,

$$t_b = 68\text{°F} - \frac{6.03 \text{ Btu/h ft}^2}{0.34 \text{ Btu/h °F ft}^2} = 68 - 17.8$$
$$= 50.2\text{°F}$$

Consulting NOAA data for Salem, Oregon, 50.2°F, although based on January insolation, is closest to the daily average temperature for the months of April and October. ■

EXAMPLE 11.1, PART H Annual SSF Based upon the Load Collector Ratio (LCR) What is the annual SSF?

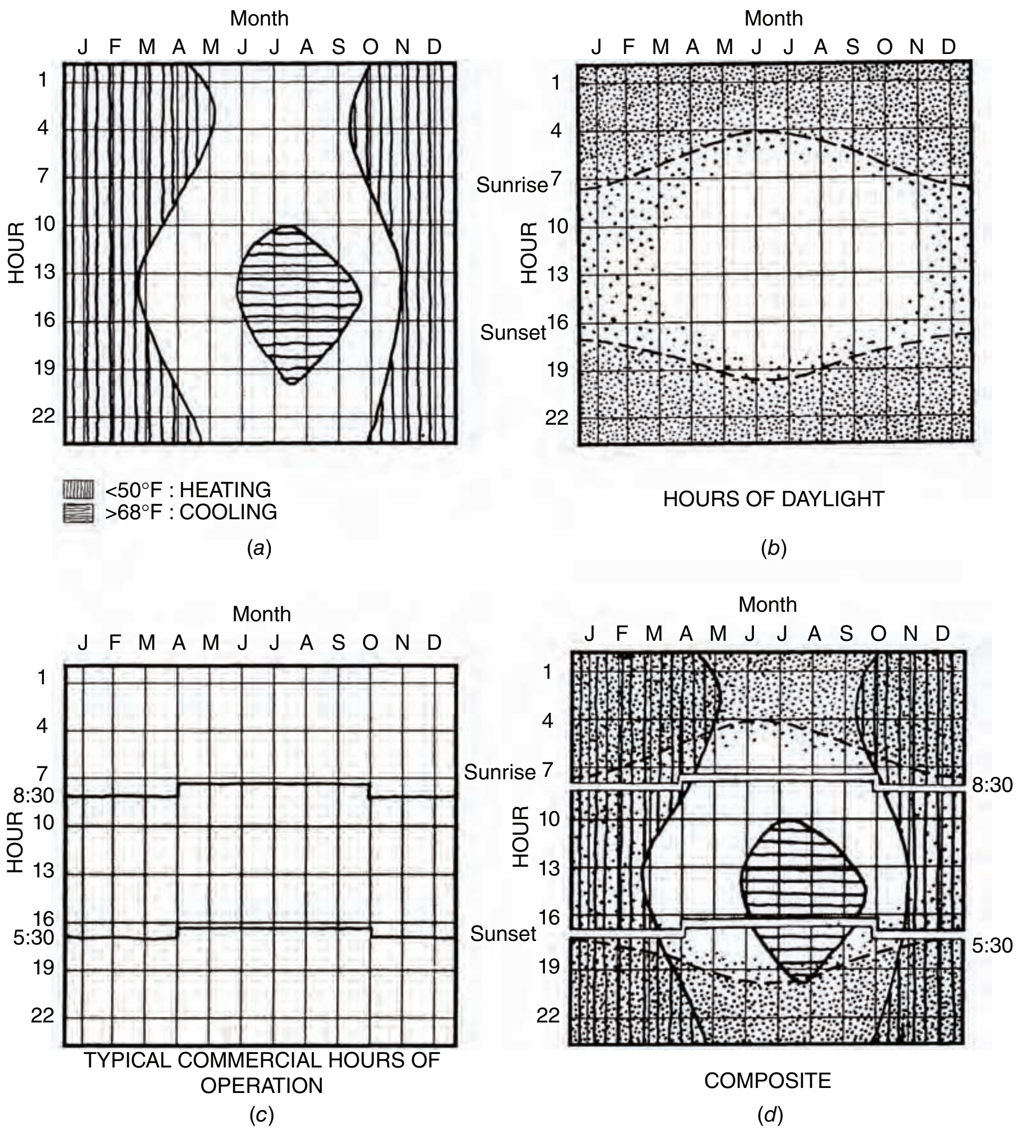


Fig. 11.4 *A series of climate timetables was prepared while designing the office building for the EPUD building. (a) Average outdoor temperatures show little daily variation in winter but a large daily range in summer. (b) Daylight peaks around noon near the summer solstice. (c) Work schedule shows the impact of summer's daylight saving time. (d) A composite timetable indicates that daylight is available during almost all working hours and that half of the hottest hours occur after the building closes on summer afternoons—thanks to daylight saving time. Cool nighttime temperatures make night ventilation of thermal mass an attractive cooling option. (Courtesy of Equinox Design, Inc., and WEGroup, PC, Architects, Eugene, OR.)*

SOLUTION

The reference passive system most closely corresponding to the DG in a typical bay is found in Table I.1, Part D. DGC1 has a high thermal storage capacity, based on an average thermal mass thickness of 4 in., and a ratio of mass to south glass area of 6:1. It has standard-performance double-glazed windows with no night insulation. (From Table 11.2, the actual building's mass to south glass area ratio is 2232 ft^2/229 ft^2 = almost 10:1.) The BLC of the typical bay is

$$24 \text{ h/day} \times (42 + 25 + 72 + 174 \text{ infiltration}) \text{ Btu/h °F} = 7512 \text{ Btu/DD}$$

The LCR of the typical bay is therefore

$$\frac{7512 \text{ BLC}}{229 \text{ ft}^2 \text{ collector area}} = 32.8$$

From Table I.3, for Salem, Oregon, with LCR = 33, system DGC1, SSF = about 27%, compared to the design guideline (Example 11.1, Part C) of SSF = 25%.

Note that if superior-performance windows had been used throughout the typical bay, the BLC would be reduced. The north window UA would become 97 ft^2 × 0.30 Btu/h ft^2 °F = 29. Thus BLC =

$$24 \text{ h/day} \times (42 + 25 + 29 + 174 \text{ infiltration}) \text{ Btu/h °F} = 6480 \text{ Btu/DD}$$

The passive system now closest to the actual building is DGC2, with triple-glazed, thus lower U-factor, openings. The new LCR is

$$\frac{6480 \text{ BLC}}{229 \text{ ft}^2 \text{ collector}} = 28.3$$

Therefore, with DGC2 in Salem, Oregon, with LCR of 28.3, find SSF as follows:

At LCR 25, SSF = 41; at LCR 30, SSF = 37 (from Table I.3)

Salem SSF range 41 − 37 = $\Delta 4$

Salem LCR range 30 − 25 = $\Delta 5$

(Actual LCR) − (Salem minimum LCR) = 28.3 − 25 = 3.3; therefore, to find the percentage difference

3.3 ($\Delta 4/\Delta 5$) = 2.6%, to be subtracted from the high SSF value.

Actual SSF = 41 − 2.6% = 38.4%

This is a substantial improvement that increases the energy saved by about 50%. ■

EXAMPLE 11.1, PART I Clear January Day Indoor Temperature Swing Find the clear January day temperature swing in a typical bay.

SOLUTION

STEP 1. (Appendix C) Salem's average January outdoor temperature = 39°F.

STEP 2. (Fig. 9.17*a*) At 44°N latitude, using a DG system, with LCR = 33, Δt solar = 24 Fdeg.

STEP 3. Δt internal (from Example 11.1, Part G, winter, and Part H) =

$$\frac{7.9 \text{ Btu/h ft}^2 \times 1440 \text{ ft}^2 \times 9 \text{ h/day}}{7512 \text{ Btu/DD} + (229 \text{ ft}^2 \times 0.74 \text{ Btu/h ft}^2 \text{ °F} \times 24 \text{ h/day})}$$

$$= \frac{102{,}384}{11{,}579} = 8.8 \text{ Fdeg}$$

STEP 4. Average January clear-day temperature indoors is 39°F + 24 Fdeg + 8.8 Fdeg = 72.8°F (within the comfort zone).

STEP 5. (Table 9.8) Indoor temperature swing, for DG with a 9:1 ratio of mass to south glass area = 0.37 × Δt solar:

$$0.37 \times 24 \text{ Fdeg} = 8.9 \text{ Fdeg } (\Delta t \text{ swing})$$

Therefore, the clear January day interior will vary by 8.9 Fdeg/2 on either side of the average temperature:

$$72.8 + 8.9/2 = 77.3\text{°F high}$$
$$72.8 - 8.9/2 = 68.4\text{°F low}$$

representing a quite comfortable range. Since the Pacific Northwest is largely overcast in winter, the daily range typically will be less wide, but the Δt solar will also be smaller. Thus, the average January day indoor temperature will be lower. ■

EXAMPLE 11.1, PART J Detailed Night-Cooling of Mass Calculation How much heat will be removed, and what is the final thermal mass temperature, in a typical bay? Assume that only the exposed surfaces of the thermal mass participate in night flush cooling. (In the actual building, the interior surfaces of the continuous cores in the precast floor slabs are also flushed with night air, yielding added cooling capacity.)

SOLUTION

STEP 1. The design temperature for Eugene, Oregon, is 89°F (Table B.5), with a mean daily range of 31 Fdeg. This is distributed by hour (using the sine curve equation) as shown in Table 11.3, with the minimum daily temperature assumed at 4:00 A.M. and the maximum at 4:00 P.M.

STEP 2. The 24-hour heat gain is estimated from Example 11.1, Part D. During the 9-hour workday, the heat gains total 13 Btu/h ft^2. During the unoccupied hours, there are negligible gains from electric lighting, people and equipment, windows, or ventilation. However, the opaque envelope gains remain because this envelope stores heat and releases it gradually. These unoccupied gains (from Table 11.2) total 0.26 Btu/h ft^2 from the walls, plus 1.03 Btu/h ft^2 from the roof, totaling 1.29 Btu/h ft^2.

Occupied:

$$9 \text{ h} \times 13 \text{ Btu/h ft}^2 = 117 \text{ Btu/ft}^2$$

Unoccupied:

$$15 \text{ h} \times 1.29 \text{ Btu/h ft}^2 = 19.35 \text{ Btu/ft}^2$$
$$\text{Daily gains} = 117 + 19.35 = 136.35 \text{ Btu/day ft}^2$$

TABLE 11.3 Oregon Office Building (Fig. 11.2) Performance: Cooling by Night Ventilation of Thermal Mass for a Typical Second-Floor Bay (use Table 10.5 and procedure to fill in values)

A. Mass surface area	2232 ft^2
B. Mass heat capacity	16,573 Btu/°F
C. Floor area (supplementary cooling)	360 ft^2
Total building (bay) volume	22,900 ft^3

(I) Hour	(II) Outside Air Temperature (°F)	(III) Cooling[a] (Btu/h)		(IV) Mass Temperature (°F)
P.M.				
8	80	No heat removed		80
9	77	(80 – 77) 2232 (line A)	= 6696	$80 - \frac{6696}{16{,}573 \text{ (line B)}} = 79.6$
10	74	(79.6 – 74) 2232	= 12,499	$79.6 - \frac{12{,}499}{16{,}573} = 78.8$
11	71	(78.8 – 71) 2232	= 17,410	$78.8 - \frac{17{,}410}{16{,}573} = 77.7$
12	68	(77.7 – 68) 2232	= 21,650	$77.7 - \frac{21{,}650}{16{,}573} = 76.4$
A.M.				
1	65	(76.4 – 65) 2232	= 25,445	$76.4 - \frac{25{,}445}{16{,}573} = 74.9$
2	62	(74.9 – 62) 2232	= 28,793	$74.9 - \frac{28{,}793}{16{,}573} = 73.2$
3	60	(73.2 – 60) 2232	= 29,462	$73.2 - \frac{29{,}462}{16{,}573} = 71.4$
4	58	(71.4 – 58) 2232	= 29,909	$71.4 - \frac{29{,}909}{16{,}573} = 69.6$
5	60	(69.6 – 60) 2232	= 21,427[b]	$69.6 - \frac{21{,}427}{16{,}573} = 68.3$
6	62	(68.3 – 62) 2232	= 14,062	$68.3 - \frac{14{,}062}{16{,}573} = 67.5$
7	65	(67.5 – 65) 2232	= 5580	$67.5 - \frac{5580}{16{,}573} = 67.2$
8	68	Stop flush: mass temperature is now below outdoor temperature		

D. Total mass cooling	212,933 Btu
E. Final mass temperature	67.2°F
F. Supplementary cooling	10,368 Btu
G. Total cooling (212,933 + 10,368)	223,301 Btu
H. 24-h heat gain	196,344 Btu
I. Flow rate required for night ventilation	About 5.5 ACH

[a]A surface conductance of 1.0 Btu/h ft^2 °F is assumed in this calculation.

[b]At this point, enough heat has been removed to meet the typical bay's design-day heat gain.

For the entire typical bay (enter on line H),

$$136.35 \text{ Btu/day ft}^2 \times 1440 \text{ ft}^2 = 196{,}344 \text{ Btu/day}$$

STEP 3. The area of exposed mass, from Table 11.2, totals 2232 ft^2. The concrete floor is covered by carpet and is therefore assumed to be disconnected from thermal storage for this space. The wallboard interior surfaces of the exterior walls are also ignored.

STEP 4. The mass heat capacity is estimated assuming that all elements are solid concrete at 150 lb/ft^3 and 4 in. deep. The bearing walls are 8 in. thick, exposed on both sides, with concrete fill in the cores of all concrete blocks. The beams are 8 in. thick, but their inner faces are unexposed (they form the air duct for the night flush system). The precast ceiling slabs are 10 in. thick, but much of this thickness consists of air-filled cores; therefore, only the lower 4 in. are assumed to participate as "exposed" mass. From Table 10.6:

$$\begin{aligned}\text{mass heat capacity} &= 2232 \text{ ft}^2 \times 0.33 \text{ ft} \times 22.5 \text{ Btu/ft}^3\ °\text{F}\\ &= 16{,}573 \text{ Btu/°F}\end{aligned}$$

STEP 5. Little supplementary cooling is assumed, although the carpeted floor provides some (albeit insulated) mass, as does the wallboard surface of the exterior walls. Assuming that only one-fourth of the floor area contributes to cooling performance,

$$0.25 \times 1440 \text{ ft}^2 = 360 \text{ ft}^2$$

STEPS 6–10. See Table 11.3.

STEP 11. Determine supplementary cooling:

$$(80°\text{F} - 67.2°\text{F}) \times 2.25 \times 360 \text{ ft}^2 = 10{,}368 \text{ Btu.}$$

STEP 12. See Table 11.3.

STEP 13. The building has more than adequate cooling capacity to meet the 89°F outdoor design condition; on typical summer days, with a high of only 83°F, there will be even more excess mass capacity. (A more conservative and very detailed analysis, assuming more electric lighting left on, extremely high temperatures, and a less-favorable coefficient of heat transfer between mass and air, led to the decision to also flush the precast cores at night.)

Because of this excess capacity, it appears advisable to begin the night flush a few hours later, when the Δt between indoors and outdoors is greater and therefore more cooling is achieved per hour of fan operation. (Repeat the procedure, beginning the flush at midnight with a Δt of 80 – 68 = 12 Fdeg, to see how similar results can be obtained with 3 fewer hours of fan operation.) The disadvantage is that the interior will remain hotter for a longer period in the evening, which could cause discomfort for a late worker. Alternatively, the flush could be stopped after 5:00 A.M., by which time the stored heat has been removed.

STEP 14. The airflow required will be checked at 4:00 A.M., the hour of maximum cooling:

$$\frac{29{,}909 \text{ Btu/h}}{0.018 \text{ Btu/ft}^3\ °\text{F h} \times (71.4\text{–}58) \text{ F deg}} = 124{,}000 \text{ cfh}$$

$$\text{ACH} = \frac{124{,}000 \text{ cfh}}{22{,}900 \text{ ft}^3} = 5.41$$

which is somewhat more than the 4.47 ACH predicted by the design guideline in Exercise 11.1, Part F. ■

11.3 PROJECT PERFORMANCE

The advantages of this passive cooling approach compared to conventional mechanical cooling can be seen in a comparison of several August monthly records for the (conventional) compressors and the night-flush fans. Figure 11.5 shows two Augusts of operation (1989, 1990) when the building operated as a night-ventilated structure. In a third August (1991), due to a building-wide computer control changeover, the building operated only as a conventionally cooled structure. The sun's impact on the building was thought to be relatively similar for these 3 months, but outdoor temperature varied as shown by the CDD values. Not only was as much electricity required to cool the conventionally operated building in 1991, despite lower temperatures than the previous August, but all the fan energy use and almost all the compressor energy use occurred during the daytime hours of high consumption. In many locations, utilities charge more for electricity used during the daytime. With night ventilation, the fans deliver huge quantities of fresh air off-peak by night, unlike the conventional daytime operation that recycles some air to save energy.

11.4 PROJECT SUMMARY

As seen in this example, combining strategies is not a linear process. Daylight influences form; form changes the amount of solar access; choice

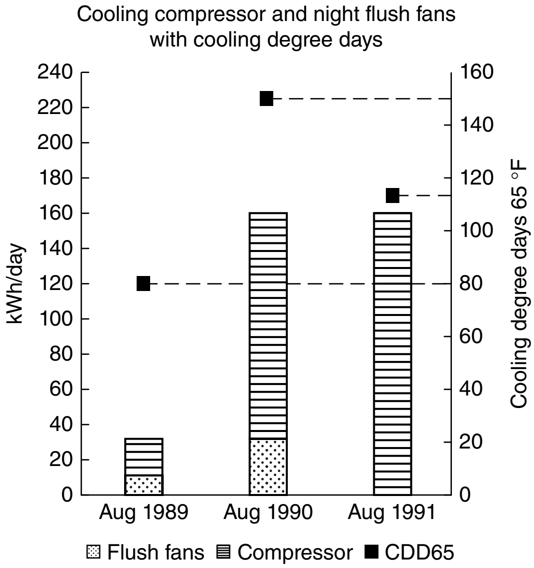


Fig. 11.5 *Comparing night ventilation of mass with conventional compressive cooling. The Emerald People's Utility District offices are monitored for end use of electricity. In August 1991 (117 CDD65 [65 CDD18]), with compressive cooling only, 160 kWh/day of electricity was used, nearly all of it during periods of heavy use (daytime). Compare this to the hotter August 1990 (150 CDD65 [83 CDD18]), when 126 kWh/day was used for compressive cooling by day, plus 34 kWh/day for night ventilation fan-forced cooling. (From Ashley and Reynolds, 1994.)*

of materials and construction methods impact heat flow; strategically placed thermal mass impacts when a space will become too cold or too warm—all of this toward achieving thermal and visual comfort. Passively cooled or heated spaces generally rely on the occupants to adapt to wider thermal fluctuations in the environment, as opposed to conditions in mechanically controlled spaces. The designer must balance thermal, visual, and acoustic conditions that contribute to our health and well-being.

Thermal comfort is represented by a fairly unified theory in which the interrelationships of environmental and personal variables are defined and quantified; however, visual and acoustical comfort variables are not so well developed or researched. The visual and acoustical comfort pictures are complex: If one variable changes, the impact on other variables is unclear, and there are no guarantees of comfort. For example, if daylight and electric light are integrated, is glare necessarily eliminated by adequate illuminance and color rendering? Visual comfort can also mean providing a connection to the outdoors and visual stimulation through the use of view windows. Acoustic comfort in an open office plan may require enclosed conference spaces for meetings, or acoustical paneling to baffle ambient sounds and conversations.

A focus on visual and acoustical comfort is no less important to building design, but the information available to the designer is not as well integrated or standardized. The designer can begin to understand the complexities of these situations by examining issues individually and then integrating concerns via the design process.

11.5 CASE STUDY—DESIGNING FOR PASSIVE HEATING AND COOLING

Manitoba Hydro Place, Winnipeg, Manitoba, Canada

Project Basics

- Location: Winnipeg, Manitoba, Canada
- Latitude: 49.9°N; longitude: 97.1°W; elevation: 740 ft (225.6 m) above sea level
- Heating degree days: 10350 base 65°F (5750 base 18.3°C); cooling degree days: 1819 base 50°F (1011 base 10.0°C) for Winnipeg, MB; annual precipitation: 19 in. (483 mm)
- Building type: New construction; commercial offices and interpretive center
- Size: 823,535 ft^2 (76,508 m^2)
- Date completed: 2009
- Client: Manitoba Hydro
- Design Team: KPMB Architects (design architects), Smith Carter Architects and Engineers (architects of record), Prairie Architects Inc. (advocate architects), Transsolar (Energy/Climate Engineers)

Background. Using high-performance, low-impact, active and passive green systems, while simultaneously maintaining high standards in design quality and human comfort, KPMB Architects designed Manitoba Hydro Place as an iconic prototype challenging the potentials of sustainable architecture. Concern for multifunctional passive systems,

Fig. 11.6 *Aerial view of north elevation showing solar chimney. (© Maris Mezulis; used with permission.)*

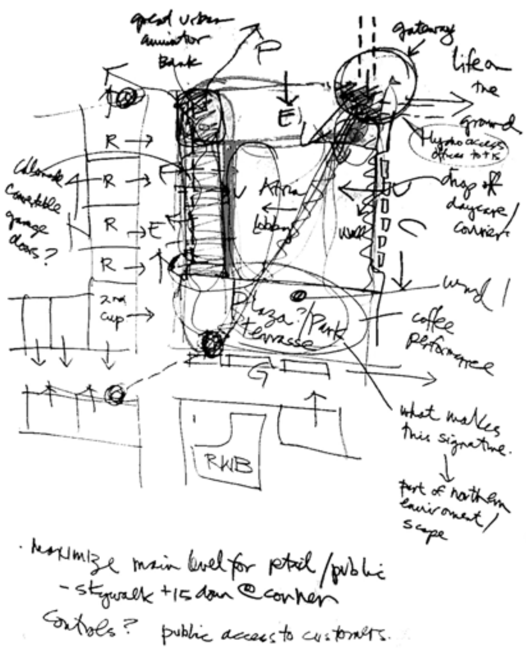


Fig. 11.7 *Conceptual sketch developed from the first charrette (© KPMB Architects; used with permission.)*

Fig. 11.8 *Street view of Manitoba Hydro Place showing tower above the podium and the solar chimney rising above the office tower roof. (© Maris Mezulis; used with permission.)*

(*a*) (*b*)

Fig. 11.9 *(a) One of three six-story south atrium wintergardens. (© Maris Mezulis; used with permission.) (b) Six-story atrium. (© Maris Mezulis; used with permission.)*

Fig. 11.10 *Detail of wintergarden water element. (© Maris Mezulis; used with permission.)*

Fig. 11.11 *Solar chimney detail. (© Maris Mezulis; used with permission.)*

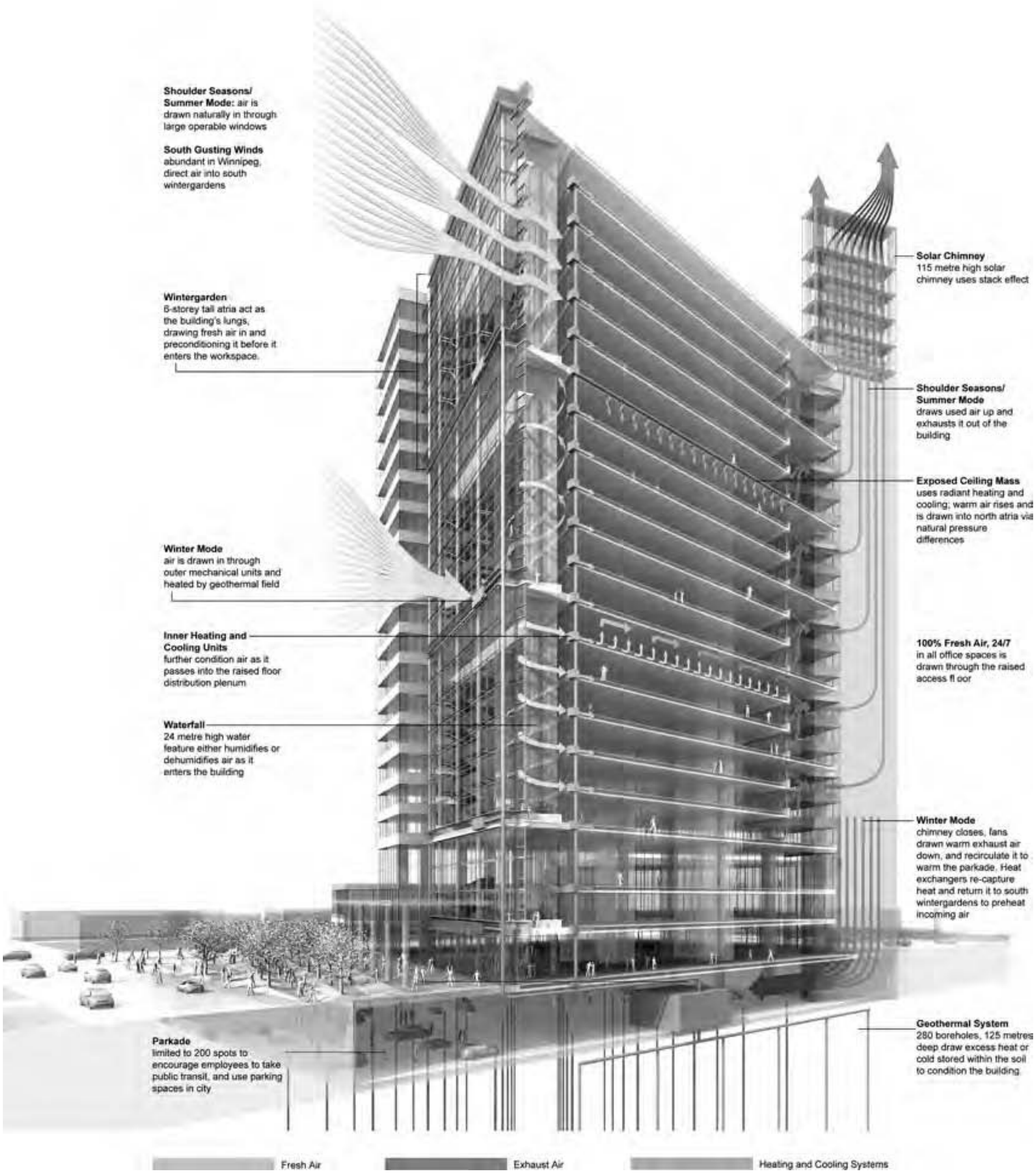


Fig. 11.12 *Natural airflows through the building (by Bryan Christie Design; © KPMB Architects; used with permission.)*

high-performance active systems, intelligent building management networks, and green management policies, among other factors, allowed Manitoba Hydro Place to achieve a high level of sustainable performance in many areas. Design principles, client values, and integrated as well as interdisciplinary design processes were important to the success of the project.

Context. Producing most of its electricity through renewable sources, Manitoba Hydro is the province of Manitoba's primary energy utility company. Manitoba Hydro Place, the company's headquarters, was built on a remediated site in a dense part of downtown Winnipeg. The structure, designed to support the company's current as well as predicted future needs, was to be the largest office building in Winnipeg at the time of construction. Despite its size, Manitoba Hydro set the goal that the building should achieve at least 60% energy efficiency, while still maintaining user comfort and design quality, when weighed against a comparable office building.

Design Intent. The new headquarters was designed not only to serve Manitoba Hydro's programmatic needs, but also to function as a model for low-impact, high-performance, sustainable architecture. The design was to use a mix of passive, active, and intelligent systems, combined with specific green policies and urban integration. The building was to respond to the climate, the city and downtown, user habits, local vegetation, soils, views, solar orientation, and functional requirements.

The leading principles during the design process were as follows:

- Create a model prototype for low-impact, high-performance architecture.
- Achieve energy saving goals and cost effectiveness, and attain at least LEED Gold certification.
- Use mix of passive/active systems.
- Respond to climate.
- Create a workplace that is functional, connective, and supportive of a sustainable lifestyle.
- Support/stimulate urban revitalization of downtown.
- Integrate within the existing transportation system of downtown Winnipeg.

Design Criteria and Validation. The end goal of the building was to achieve energy and water conservation, while also establishing an integrated hub that promoted sustainable living on a number of scales. An interdisciplinary and integrated design process was key to testing and optimizing the project's aims. Aside from the architectural actors involved, specialist engineers and consultants from a wide range of disciplines were called upon—including structural, mechanical, electrical, geothermal, building envelope, microclimate, traffic/parking, water, and geotechnical consultants, among others. A combination of computer simulations and real-model tests were conducted in order to verify the capacities and capabilities of the passive and active systems to be employed.

Post-Occupancy Validation Methods. Manitoba Hydro established a monitoring system in order to verify the building's performance over a two-year period following full occupancy. The building uses an intelligent building management system in order to regulate its ventilation, heating, and lighting systems. For its success in achieving its goals, the company credits the ground-source heating/cooling system, solar chimneys, wintergardens, automated shading systems, high-performance and intelligent lighting systems, ventilation systems, and management policies, among other factors.

Design Process Specifics. The Integrated design process utilized in the design and construction of Manitoba Hydro Place was based on the C-2000 Program for Advanced Commercial Buildings, designed by a branch of the Canadian government (Natural Resources Canada). Key steps in the process were as follows:

An integrated design team was formed, composed of the client, architects, engineers, consultants, cost estimators, and contractors. Manitoba Hydro worked with KPMB in order to form this team.

- Before the design of the project began, a project charter was formed, establishing the primary goals (see Design Intent) to be achieved.
- One year was set aside in order to form a critical design concept for the new building, involving charrettes and workshops, among other activities.
- During the design development phase, bi-weekly meetings and charrettes were also held, for discussing and resolving the issues

brought up by the interdisciplinary actors involved.
- The contracting and bidding phases were coordinated earlier in the process; through this method, material/labor costs and schedules were confirmed far ahead of time, allowing the interdisciplinary design team to avoid any surprises in terms of material costs or labor supply during actual construction.

Performance Data. Information available to date suggests substantial success in a range of critical sustainability fields—particularly in the areas of energy conservation, water-use reduction, and material use.

- Manitoba Hydro was awarded LEED Platinum certification in May of 2012.
- The building achieved an energy cost savings of 70% when weighed against a comparable office tower constructed according to the building standards specified by the Model National Energy Code.
- Through the use of aerator faucets, dual-flush toilets, and waterless urinals, water use was reduced by 43%.
- The building uses a 100% fresh air ventilation system.
- Throughout the construction phases, 85% of wastes were recycled or salvaged; over 23% of new materials contained recycled content; and 33% of new construction materials were extracted within an 800-km distance from the site, or transported via railway within a 2400-km distance from the site.
- Manitoba Hydro provides 16 vehicles, 11 of which are hybrids, for employee use.
- A reduction in heat island effect was achieved through the implementation of reflective roofing or green roof systems.
- The building was named one of the AIA/COTE Top Ten Green Projects in 2010; it was given the Urban Land Institute Global Award for Excellence in 2012; it also received the Best Tall Building Award in the Americas category via the Council for Tall Buildings and Urban Habitat in 2009.

FOR FURTHER INFORMATION

Canada Newswire. 2012. "Manitoba Hydro Sets New Record with LEED Platinum," May 25, 2012: http://www.newswire.ca/en/story/980643/manitoba-hydro-place-sets-new-record-with-leed-platinum

KPMB Architects: http://www.kpmb.com/

Natural Resources Canada: http://www.nrcan.gc.ca/home

Prairie Architects: http://www.prairiearchitects.ca/

Prairie Architects, "Manitoba Hydro Place: Eco Facts": http://www.prairiearchitects.ca/files/Hydo_features_pamphlet-11x8.5_v2.pdf

Smith Carter Architects Inc.: http://www.smithcarter.com/

Smith Carter Architects, 2010. "Case Study: Manitoba Hydro Place," April 15, 2010: http://www.smithcarter.com/green/resource/Media/Hydro_Case_Study_April2010.pdf

Transsolar Energietechnik GMBH: http://www.transsolar.com/

References and Resources

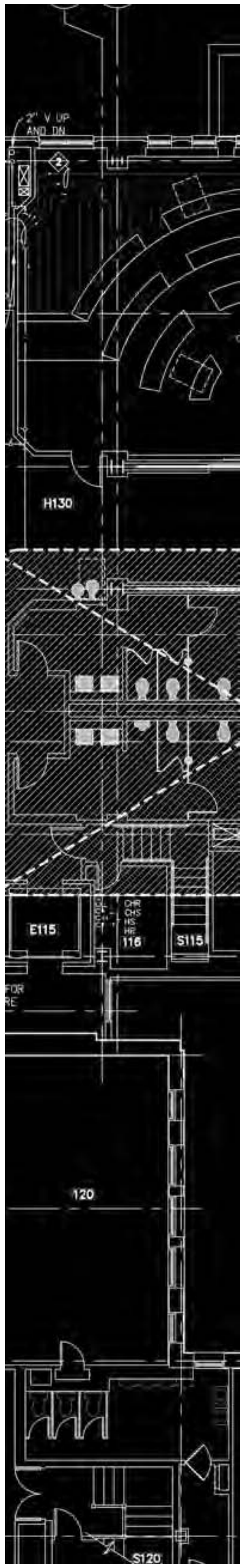
Ashley, R. and J. Reynolds. 1994. "Overall and Zonal Energy End Use in an Energy Conscious Office Building." *Solar Energy*, Vol. 52, No. 1, pp. 75–83.

Emerald People's Utility District. www.epud.org/

University of Oregon seminar. 1999. "EPUD REVISITED: A Post Occupancy Analysis of Thermal and Daylight Design Implementation," Vital Signs case study by University of Oregon ARCH 407/507 seminar. http://pages.uoregon.edu/akwok/VSCS/

P A R T   I V

ACTIVE ENVIRONMENTAL SYSTEMS



In Part III (Passive Environmental Systems), daylighting, passive solar heating, and passive cooling systems were discussed as effective, energy-efficient environmental control approaches. In many buildings, as a result of climate or function, there is a need to supplement passive strategies with active systems. The chapters composing Part IV: Active Environmental Systems address heating and cooling (HVAC) systems, electric lighting fundamentals and design, and water and waste systems. These active systems are typically designed by consultants, use specialized components, and require purchased energy (or water) resources. Information to support informed decision making regarding components and systems is presented with example problems and guidelines. The interconnectivity of the thermal, luminous, and aqueous environments will vary depending upon the climatic conditions of the site/region, occupancy, function, behavioral activities and attitudes, and the quality of the building materials and enclosure. It is critical that these systems be optimized to conserve resources.

CHAPTER 12

Active Climate Control

ACTIVE CLIMATE CONTROL SYSTEMS are thermal comfort and indoor air quality modification systems that: (1) require the use of purchased energy, (2) involve numerous single-purpose components, (3) are typically only lightly integrated into the overall building fabric, and (4) are normally designed by a consultant other than the architect. They are, conceptually, the opposite of a passive systems approach to climate control. Although this book exhibits a preference for passive solutions, the use of active systems is very commonly dictated by realities of climate or building function. A designer of buildings virtually anywhere in the world should be familiar with active systems (for climate control, lighting, vertical circulation, fire protection, and sanitation)—they are a part of modern design.

The acronym *HVAC* is typically used to describe an active climate control system. HVAC stands for heating, ventilating, and air conditioning. Heating is a process whereby the temperature of something (such as the air in a building) is increased. Ventilation is a process that moves or circulates air. It would be easy to assume that the *AC* part of *HVAC* refers to "and cooling." This would be incorrect—*AC* stands for air conditioning, which has very specific process requirements. An air-conditioning system should be able to: (1) control air temperature (by heating and/or cooling as required), (2) control the humidity of air (perhaps bi-directionally), (3) control air distribution (speed and direction), and (4) control indoor air quality (IAQ). If it sounds as if the term AC generally covers the expectations of the term HVAC, this is true. AC is commonly used as a synonym for HVAC and vice versa.

The term HVAC will be used in this chapter, for consistency with usage in the design professions. Occasionally, a project may demand only a heating system, or only a ventilation system, or only a cooling system—more typically, however, today's projects demand (or at least expect) air conditioning as provided by an HVAC system. Ideally, the capabilities of the passive climate control systems discussed in Chapters 8 to 11 would be considered first. Even when a passive system cannot fully provide for project requirements, such an approach might be used during part of the year or in some part of a building to mitigate the energy and carbon impacts that come with active systems.

12.1 INTRODUCTION

The process of acquiring a viable HVAC system parallels the process of acquiring a building and generally involves decisions and actions taken during the predesign, design, construction, and occupancy phases of a project. The following list describes some of the key aspects of HVAC system acquisition in the order that would be typical for a new construction project. The list presumes that the commissioning process is in place (as would be expected for any high-performance project).

- Establish HVAC-related owner's project requirements (OPR: design issues/intents/criteria; including code/standard compliance).
- Establish zoning requirements.
- Make a preliminary system selection based on the OPR and zoning requirements.
- Calculate design heating/cooling loads.
- Select appropriate source equipment (to meet loads, intent, and context).
- Select appropriate distribution approach (to meet intents and fit context).
- Coordinate HVAC components with other building systems.
- Rough-size equipment (fans, pumps, valves, dampers, pipes, ducts, condensers, air-handlers, tanks, etc.).
- Run energy analyses to optimize equipment selections and system assemblies.
- Final-size equipment based upon optimization studies.
- Coordinate final individual equipment selections into a cohesive whole.
- Develop appropriate control logic and strategies.
- Develop commissioning test protocols and checklists.
- Witness systems installation and verifications.
- Develop systems manuals for the owner.
- Provide benchmark (new system) performance data for the owner.
- Assist in initial operations to maintain the owner's project requirements.

The scope and extent of the actions described here will vary from project to project. They generally apply to small and simple (single-family residence) as well as large and complex (teaching hospital) projects, but specific actions will be adapted to fit the project scale, schedule, and budget. For smaller buildings, HVAC system selection/design may be done by the architect alone (or with assistance from a mechanical contractor). For larger, more complex buildings, consulting engineers will be involved (perhaps along with other specialists such as fire protection engineers or laboratory consultants). At whatever scale, a high-performance outcome will normally be most easily achieved through an integrated design process. Several of the earlier actions in this list (specifically, developing the owner's project requirements and thermal zoning) are arguably best done by the project architect (who will likely spend the most time with the client). Other actions will be completed by a consulting engineer, yet others by a contractor, and others by the owner's operating personnel. A process that taps into the experiences and expertise of these diverse players in a timely manner simply makes sense. With inspired teamwork, the integration of HVAC services can enhance building form, as many examples in this chapter show.

Earlier chapters in this book deal with foundational considerations that feed into HVAC systems design. Chapter 1 addresses the design process and the many influences on that complex activity (such as design intent and codes/standards) that may impact HVAC system and equipment selection. Chapter 2 deals with environmental resources, which are a consideration in all aspects of building design. Chapter 3 addresses sites and their resources, which will affect building heating/cooling loads and the selection of appropriate systems solutions. Chapter 4 deals with comfort, the thermal aspects of which will be a major element of an owner's project requirements for virtually all building types. Chapter 5 provides background information on indoor air quality. Along with comfort, acceptable IAQ will be an intended outcome for most projects. Chapters 6 and 7 present the fundamentals of building thermal envelope design and performance—which will affect the loads that an HVAC system must mitigate. Chapters 9 and 10 present passive heating and cooling systems as preferred starting points for climate control. Chapter 11 discusses integration of passive heating, cooling, and lighting systems.

A potential problem faced by one attempting to understand HVAC systems is their seeming complexity. HVAC system types are numerous, their components are more numerous, and the expected system outcomes can vary widely. This is unavoidable as such diversity permits these systems to work in a wide range of contexts while providing some flexibility in selection. Fewer options would ease understanding—but would be unacceptable to the design professions, which thrive on choice. An attempt has been made to chunk and lump the aspects of HVAC systems presented in this chapter, to facilitate initial engagement with the systems. First, however, comes an introduction to some basic concepts.

12.2 HISTORY AND CONTEXT

One of the most basic functions of a building is to provide shelter from weather. In the words of James Marston Fitch: "to interpose itself between people and the natural environment . . . to remove the gross environmental load from their shoulders" (Fitch 1999). Historically, this role was accomplished through passive systems—for heating, cooling, and daylighting. In a carefully designed building, the roofs, walls, windows, and interior surfaces alone can maintain comfortable interior temperatures for most of the year in most North American climates. With appropriate scheduling, the most uncomfortable hours within buildings can often be avoided; for example, the siesta avoids the hottest afternoon hours within stores and office buildings. Several aspects of comfort and climate, however, pose difficult challenges for ordinary building forms and materials. Under these circumstances, when passive systems were the only available solutions, human comfort and well-being suffered. Active systems provide another option.

A building surface influences comfort primarily through its *surface temperature*; secondarily, a surface can modify *air temperature* (as when cool air moves across a warm surface). As important as these two determinants of comfort are, they are often not sufficient by themselves. In cooling situations, *air motion* and *relative humidity* are significant comfort determinants. For most building occupancies, *air quality* is an important issue under both heating and cooling conditions.

Building form can work with climate to produce air motion for cooling, although the higher air speeds that can extend the human comfort zone may be difficult to provide without mechanical assistance. Relative humidity is most readily controlled by mechanical or chemical means. Building form and materials may be able to keep spaces surprisingly cool, but without dehumidification, surfaces in many North American summer climates can become clammy and covered with mold. Further, it is difficult to filter air for IAQ purposes without a fan to force the air through the filtering medium.

Thus, whereas air and surface temperatures can often be successfully manipulated by passive means (a combination of building form, surface material, and informed user response) the comfort determinants of air motion and relative humidity, and the health and comfort considerations of air quality, often require mechanical systems. As the control of air properties—motion, moisture, pollutant content—becomes more critical to project success, the designer becomes more likely to respond with a sealed building, excluding outdoor air except through carefully controlled mechanical equipment intakes. In the recent past, this exclusion of outdoor air has often been accompanied by the exclusion of daylight, of view, of solar heat on cold days—in sum, by a general rejection of all aspects of the exterior environment. As designers come to terms with the role of mechanical systems in high-performance buildings, they should also clarify the role of these systems in reaching net-zero energy or carbon-neutral outcomes. Passive systems can be historic, but have limitations. Active systems are more recent and seem to have few if any limits on capabilities, but do have serious environmental impacts.

Depending upon how one interprets the definition of an active system, it is reasonably fair to claim that active heating systems have been in use for a rather long time. Roman hypocaust systems exhibit basic characteristics that mirror today's central hot air heating systems. Such sophistication was generally lost for almost two millennia until scientifically designed central heating systems reappeared in the 1800s. Rationally designed central ventilation systems also appeared in the early to mid-1800s. Design methods and component analyses were documented in early heating/ventilating texts (see, for example, the timeline from Haberl et al., 2012). The cooling part of an active climate control system is a much more recent development. Early forays into central cooling occurred in the mid-1800s, but true diffusion of active cooling into the building sector came only after the Second World War.

As active climate control systems became commonplace and found increasing use in a range of building types, they also became more complex and more specialized. This has resulted in a specialization and compartmentation of design responsibilities that mirror the situation in many other aspects of design, and modern life in general. Current terminology describes this as working in separated silos or towers. As suggested in Chapter 1, a relay-race-like, non-integrated design process seldom serves the long-term interests of the owner and places roadblocks in the path to high-performance building outcomes. A fully integrated design process is strongly recommended. If this is not yet feasible on a specific project, then the commissioning process is suggested as a bridging mechanism. The ongoing collaborative work of the commissioning team (composed of diverse project participants) can provide some of the benefits of a fully integrated process—and is well documented and well accepted in many parts of the world. It is unreasonable for important aspects of building design to remain a mystery or appear to be magic to other design team participants.

12.3 RELEVANT CODES AND STANDARDS

The role of codes, standards, and guidelines in the design of an HVAC system is quirky, but consistent with the pattern seen in other areas of building design. In the United States there is rarely a code mandate that requires that an HVAC system be provided for a building. There may be requirements here and there that dictate that building occupants not be allowed to freeze in winter (we seem less concerned as a society about summer heatstroke), but there is no known code requirement that U.S. buildings be thermally comfortable. Increasing adoption of ASHRAE Standard 62.1 is moving the profession toward provision of code-mandated minimum air quality. Once a decision has been made to provide an HVAC system, however, all sorts of codes, standards, and guidelines come into play. These may address the design and installation of specific components or equipment (such as boilers, flue stacks, or window air-conditioning units), the arrangement and installation of systems (primarily from the perspective of life safety and energy), and the overall performance of a system (mainly its energy performance).

It would be unreasonable to attempt to list in this chapter all the design guidance documents that would apply (in the United States) to an HVAC system and its components. If the geographic perspective is widened to systems designed worldwide, the number of applicable standards and guidelines mushrooms to easily exceed a thousand documents. Chapter 39 of the 2013 *ASHRAE Handbook—Fundamentals* provides an extensive and up-to-date listing of HVAC-applicable codes and standards sorted by subject (ASHRAE, 2013). Some of the more important and commonly encountered standards and guidelines include:

- ASHRAE Guideline 0-2013, *The Commissioning Process*
- ASHRAE Guideline 1.1-2007, *HVAC&R Technical Requirements for the Commissioning Process*
- ASHRAE Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings*
- ASHRAE Standard 62.1-2013, *Ventilation for Acceptable Indoor Air Quality*
- ASHRAE Standard 62.2-2013, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*
- ASHRAE Standard 55-2013, *Thermal Environmental Conditions for Human Occupancy*
- USGBC: LEED rating systems for various building types
- NFPA: Numerous fire protection standards (see Part VI of this book)

12.4 FUNDAMENTALS

A number of fundamental principles underlie the selection and design of an HVAC system. The most basic of these considerations are summarized herein.

(a) Design Intent and Design Criteria

The design of any building system must start with a clear understanding of the outcomes required and/or expected by the client, by users/occupants, and by society. This is certainly true for HVAC systems design. Society's expectations are typically expressed through building codes (in particular those dealing with energy and IAQ). The aspirations of the client and subsequent building users are best expressed through development of a comprehensive and cohesive statement of Owner's Project Requirements—OPR, a formal document under the ASHRAE commissioning process. A good OPR will address: thermal comfort requirements for all occupied spaces, indoor air quality requirements for all occupied spaces, minimum acceptable energy performance, environmental preferences for constituent components, first cost, life-cycle costs, reliability, maintainability, building space and volume demands, aesthetics, and other considerations. The commissioning process will verify the likelihood that the HVAC system(s) proposed, designed, and installed will be able to deliver on the performance targets established in the OPR. Selecting an HVAC system in the absence of clear selection criteria is not designing—it is wishful thinking.

(b) Thermodynamics Laws

The laws of thermodynamics apply to the design of HVAC systems and are worthy of a quick summarization and interpretation.

- Zeroth law: Two systems that are in thermal equilibrium with a third system are in thermal equilibrium with each other. This law helps to define the notion of temperature. Heat will only flow from a higher to a lower temperature.
- First law: Heat and work are forms of energy transfer. Energy is always conserved; thus, all energy associated with a system must be accounted for. Perpetual motion is impossible, and efficiencies greater than 100% are impossible. All macro energy forms within a building devolve to heat.
- Second law: A system attempts to move toward a state of thermodynamic equilibrium, which increases entropy (disorder). It takes energy to order (and maintain order within) a system, which will otherwise naturally move toward disorder.
- Third law: The entropy of a system approaches a constant value as the temperature approaches zero; this is not particularly germane to HVAC system design.

(c) Important "e" Terms

Several terms that start with the letter "e" are important to consider when designing an HVAC system. These terms include:

- Energy: Energy is the ability to do work. In HVAC system design, the amount of energy required to accomplish a defined work task is often of substantial interest to the design team. Power is an instantaneous snapshot of work (over a very short time increment); energy is the integration of power over time (per hour, per day, per year). Energy requirements may be analyzed at the site boundary of a project (effectively at the electric meter, for example), or they may be analyzed at the source of the particular energy supply (such as at the electrical power plant). These two system analysis boundaries will yield very different results. The appropriate system boundary is presently a matter of serious contention.
- Effectiveness: Effectiveness is a qualitative descriptor that describes success in meeting defined objectives. An HVAC system that delivers the Owner's Project Requirements would be properly termed effective.
- Efficiency: Efficiency is a defined ratio (output/input) that is a quantitative assessment of the ability of a system to provide some effect relative to the resource cost of doing so. An HVAC system that provides a lot of useful heat while requiring just slightly more heat as input would be termed efficient. A system can be efficient while being ineffective. Conversely, a system can be effective while being inefficient. A high-performance building seeks systems that are simultaneously effective and efficient.
- Enthalpy: Enthalpy is a measure of the total (sensible and latent) energy content of a sample of air. See Section 4.2 for further information.
- Entropy: Entropy is a measure of the disorder of a system. Without counterbalancing energy inputs, most building systems lose order over time (thus increasing in entropy). A hot water pipe loses energy when not in use. A layer of paint degrades over time. Water must be pumped to overcome the effects of gravity. Buildings continually require the input of resources for operation and maintenance.
- Exergy: Exergy is a generally not-well-understood measure of the utility of an energy exchange. In the future we may evaluate the exergy of competing HVAC system solutions to judge their appropriateness. As an example, the exergy of using a nuclear power plant to heat water by 50 degrees is quite different from the exergy involved when using a passive solar thermal system to accomplish the same task.
- In addition, one "c" term is also of interest—conservation. Conservation implies the use of less of something (energy, water, materials, cash). Conservation has both a noble history and detractors. In some circles conservation is seen as unnecessarily doing with less. Conservation is a necessary concept when efficiency makes no

sense. For example, discussing the efficiency of a showerhead is irrational (output equals input). A water-conserving showerhead is a logical way to address this situation—where there is an attempt to provide equal effectiveness using less water.

(d) Applied Psychrometrics

Psychrometrics (briefly introduced in Chapter 4) is the study and manipulation of the properties of moist air. Adjusting the properties of air (which, in a building, always contains water vapor) is precisely what the thermal side of an air-conditioning system is intended to do. HVAC systems are psychrometric systems, and a fundamental understanding of moist air properties and their modification is critical to an understanding of climate control systems. Psychrometrics, which can be addressed through equations, data tables, and/or a diagram called the psychrometric chart, is a means of understanding the relationships among various properties of air. The psychrometric chart (Fig. G.1, G.2) is commonly used as an HVAC system design tool.

As seen in Fig. 4.3, there are eight distinct psychrometric processes. These are related to commonly encountered HVAC systems in the following discussion.

Sensible heating. Under this process, room air temperature is increased with no change in absolute humidity. Relative humidity will decrease as the air is heated, but there is no change in air moisture content. This process is very common and represents the outcome of the typical building heating system, which is purely sensible and has no inherent capability to affect latent loads. Hot air heating, baseboard radiation, and solar heating systems are all sensible heating systems.

Heating and humidifying. This process, which moves up and to the right on the psychrometric chart, is often desired in smaller buildings located in cold climates. There is no single HVAC device that will produce this effect; sensible heating equipment must be paired with a humidification device.

Heating and dehumidification. This process, which moves down and to the right on the psychrometric chart, is not a commonly desired or encountered process. No single HVAC device will intentionally produce this effect (although it is possible to accomplish).

Humidification. This process adds moisture to the air without intentionally changing air temperature. A device called a humidifier can accomplish this effect (although rarely will this alone be adequate to produce thermally comfortable conditions).

Dehumidification. This process removes moisture from the air without intentionally changing air temperature. A device called a dehumidifier can accomplish this effect. This may occasionally (in benign climates) be the only effect required to produce thermally comfortable conditions.

Sensible cooling. This process reduces air temperature without a change in absolute humidity. Some HVAC systems will produce sensible cooling through a part of their operating range. Other HVAC systems (such as a radiant cooling system) are specifically designed to operate as sensible cooling devices. Most active cooling systems, however, produce sensible and latent cooling effects.

Cooling and dehumidification. This combined sensible and latent cooling process is commonly desired in a wide range of building situations and is produced by the common vapor compression cooling process. A cooling coil is brought to a temperature below the dew point of the room air such that moisture condenses and leaves the air while the air is reduced in dry-bulb temperature.

Evaporative cooling. This process, which involves simultaneous sensible cooling and latent heating (cooling and humidification), is an intriguing HVAC option. The evaporative cooling process occurs along a line of near-constant enthalpy; sensible heat is exchanged for latent heat at little net energy cost. Where climate conditions will support this process, direct evaporative cooling can be a very energy-efficient space-cooling option. Indirect evaporative cooling can be employed where high relative humidity resulting from a direct evaporative cooling process would be objectionable.

An example showing the use of the psychrometric chart to analyze conditions that occur during typical HVAC system operation may be helpful.

EXAMPLE 12.1 Find the total heat to be removed, and thus the required cooling capacity, for a dance hall. The design conditions are:

Room conditions (summer):	75°F DB (24°C), 50% RH
Number of occupants:	80 people
Activity:	Dancing
Ventilation provided:	35 cfm (18 L/s) per person
Outdoor air conditions:	90°F DB, 75°F WB (32.2 and 23.9°C)

Heat Gains in the Room 80 people dancing (see Table G.8)	Sensible Heat, SH (Btu/h)	Latent Heat, LH (Btu/h)
80 @ 305 Btu/h	24,400	
80 @ 545 Btu/h		43,600
Total transmission and solar gain, lights, equipment, etc.	67,600	None
	Room sensible heat (RSH)	Room latent heat (RLH)
	= 92,000	= 43,600
Total heat gains in room: 135,600 Btu/h (RSH + RLH)		

SOLUTION

First, determine the portion of the heat gain that is due to sensible heat gain, called the *sensible heat factor* (SHF):

$$\text{SHF} = \frac{\text{RSH}}{\text{RSH} + \text{RLH}} = \frac{92{,}000}{135{,}600} = 0.68$$

On the psychrometric chart (simplified in Fig. 12.1), draw a line between the fixed "bull's-eye" target (80°F DB, 50% RH) and the value of 0.68 on the SHF scale at the upper-right edge of the chart. This is called the *SHF line*, and its slope is of interest.

Point *A* is the condition of the air within the dance hall as it is returned to an air-handling unit for reprocessing: 75°F DB, 50% RH (62.5°F WB). The system designer must decide how much cooler the supply air should be than the room air in order to provide capacity to absorb the heat load of the dance hall. To avoid uncomfortable drafts, the supply air temperature is usually 20F° (or less) below the room air temperature. In this case a supply-to-room Δt of 20F° is chosen. The quantity of air required to sensibly cool the room is found as

$$\text{cfm} = \frac{\text{RSH}}{1.1\Delta t} = \frac{92{,}000 \text{ Btu/h}}{1.1\ (20\text{F}°)} = 4182 \text{ cfm}$$

This equation is a reformulation of the ventilation load equation: q = (cfm) (1.1) (Δt)

The portion of this required supply air that should be *outdoor* air is found as follows

$$80 \text{ people} \times 35 \text{ cfm/person} = 2800 \text{ cfm}$$

So the percentage of outdoor air is

$$\frac{2800}{4182} = 67\%$$

Several important process points can now be located on the psychrometric chart. Point *B* is the condition of the supply air entering the room; it will be 20F° below 75°F, which places point *B* somewhere on the 55° DB line. To determine exactly where, a dashed line is drawn through point *A*, *parallel* to the previously plotted SHF line, and extended until it crosses the vertical 55° DB line. This crossing point is point *B*, and occurs at 55° DB, 51.3° WB; enthalpy (h_B) = 21.0 Btu/lb. Point *D* is the condition of the outdoor air, given (under design conditions) as 90°F DB, 75°F WB.

Point *C* (Fig. 12.1*b*) represents the mixture of 67% outdoor air and 33% return air that is brought to the air-handling unit for treatment and redistribution to the dance hall. Connecting points *A* (return air) and *D* (outdoor air) and marking 67% of the distance from *A* to *D* gives point *C*. This occurs at 85°F DB, 71.3°F WB; enthalpy (h_C) = 35.2 Btu/lb.

The cooling equipment must remove the grand total heat (GTH; sensible plus latent) according to the formula

$$\text{GTH} = 4.5 \times \text{cfm} \times (h_C - h_B)$$

(where 4.5 is a constant = 60 min/h × 0.075 lb/ft^3 average air density). So, in this example

$$\begin{aligned}\text{GTH} &= 4.5 \times 4182 \text{ cfm} \times (35.2 - 21.0)\\ &= 267{,}230 \text{ Btu/h}\end{aligned}$$

The capacity of a refrigeration unit is typically specified in tons, where 1 ton = 12,000 Btu/h. The refrigeration required for this example is:

$$= \frac{267{,}230 \text{ Btu/h}}{12{,}000 \text{ Btu/h ton}} = 22.3 \text{ tons}$$

Note: If a *minimum* outdoor airflow rate of, say, 25 cfm per person was provided,

$$80 \text{ people} \times 25 \text{ cfm/person} = 2000 \text{ cfm}$$

The percentage of outdoor air becomes 2000/4182 = 48%.

Point *C* then moves to about 82°F DB, 68.8°F WB, at which point h_C = about 33 Btu/lb.

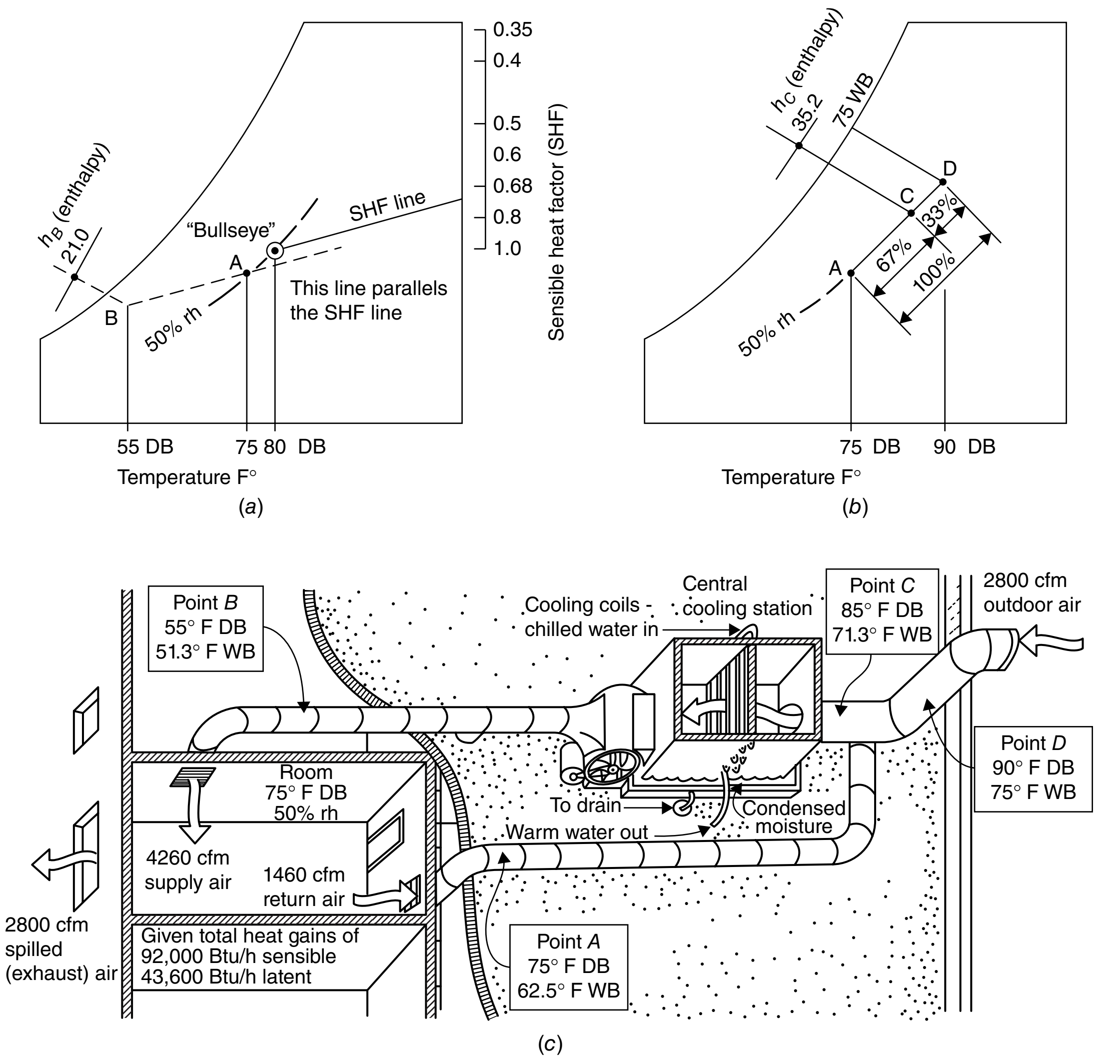


Fig. 12.1 *Sizing cooling equipment using the psychrometric chart. (a) Finding the conditions for the supply air. SI values are: 12.8, 23.9, and 26.7°C DB. (b) Finding the conditions for the return air–outdoor air mixture. SI values are: 23.9 and 32.2°C DB; 23.9°C WB. (c) Points* A, B, C, *and* D *are representative conditions within the cooling cycle. SI values are: Point* A *(23.9/16.9°C); Point* B *(12.8/10.7°C); Point* C *(29.4/21.8°C); Point* D *(32.2/23.9°C); outdoor air (1321 L/s); exhaust air (1321 L/s); supply air (2010 L/s); return air (689 L/s); room (23.9°C).*

The required refrigeration capacity then becomes

$$4.5 \times 4182 \times (33 - 21) = \frac{225{,}828 \text{ Btu/h}}{12{,}000 \text{ Btu/h ton}}$$

$$= \text{about } 18.8 \text{ tons}$$

This change in outdoor air rate would provide a first-cost saving for reduced equipment size and also energy savings over the life of the dance hall. IAQ, however, might suffer. This type of trade-off currently confronts any designer looking at the credit for additional ventilation airflow that is found in LEED-NC; a trade-off pitting energy conservation versus IAQ. ■

A focus on the psychrometrics of an active cooling process will further help explain how this tool is used. The work to be done by active air-conditioning equipment is indicated by the total change in enthalpy that must occur as the air is treated by the equipment. The psychrometric chart is used to accurately determine air-conditioner performance requirements.

First, consider the problem of determining the total change in enthalpy. Assume outdoor conditions of 90°F DB and 76°F WB, with desired indoor conditions at 75°F DB and 50% RH. From Fig. G.1, these indoor conditions equate to 75 DB/62.7 WB.

In the simple (but relatively rare) case of cooling 100% outdoor air, the total heat to be removed is determined as shown in Fig. 12.2. How much total heat will be removed in taking air from 90 DB/76 WB to 75 DB/62.7 WB?

For every pound of "dry" air (based on the weight of the air alone) that is cooled and dehumidified, 39.6 – 28.3 = 11.3 Btu must be extracted. Similarly, for every pound of air so treated, 0.0162 – 0.0093 = 0.0069 lb of condensed moisture must be disposed of.

The actual cooling process is more complex, as shown in Fig. 12.3. The conditioned air must be introduced to the space at both a lower DB temperature and lower RH than the desired indoor conditions, so that the supply air can "soak up" heat and moisture, then leave through the return air grilles at the desired indoor conditions (75 DB/50% RH). So another set of conditions, of lower DB and RH, will be established, depending upon the rates at which air is introduced and the amounts of heat and moisture to be absorbed by the air passing through the space.

Within the cooling equipment, the outdoor air follows a complex path; the lines labeled 1, 2, and 3 in Fig. 12.3 trace the sensible cooling and dehumidifying steps. Outdoor air is cooled without a loss of moisture (step 1) until it reaches saturation (its dew point). The cooling then continues; the air continues to lose sensible heat (step 2) and now loses moisture as well, extracting more heat. When step 3 begins (known as a reheating process), the less moist and lower-temperature air is heated to 65°F, 40% RH—slightly below the conditions to be maintained in the space. The changes in the heat and moisture content of the air at the various stages are measured along the enthalpy scale.

Deliberately adding heat to just-cooled (actually, intentionally overcooled) air sounds wasteful—and it is. The reheat process, however, is also a very effective thermal control mechanism. Heat-recovery processes can be incorporated in cooling equipment so that the reheat is provided by heat that was removed and would otherwise be wasted. Heat-recovery equipment is discussed in Chapter 5.

Shifting focus to heating, the process of heating outdoor air in winter is charted in Fig. 12.4. Air at low temperatures in winter often has a humidity

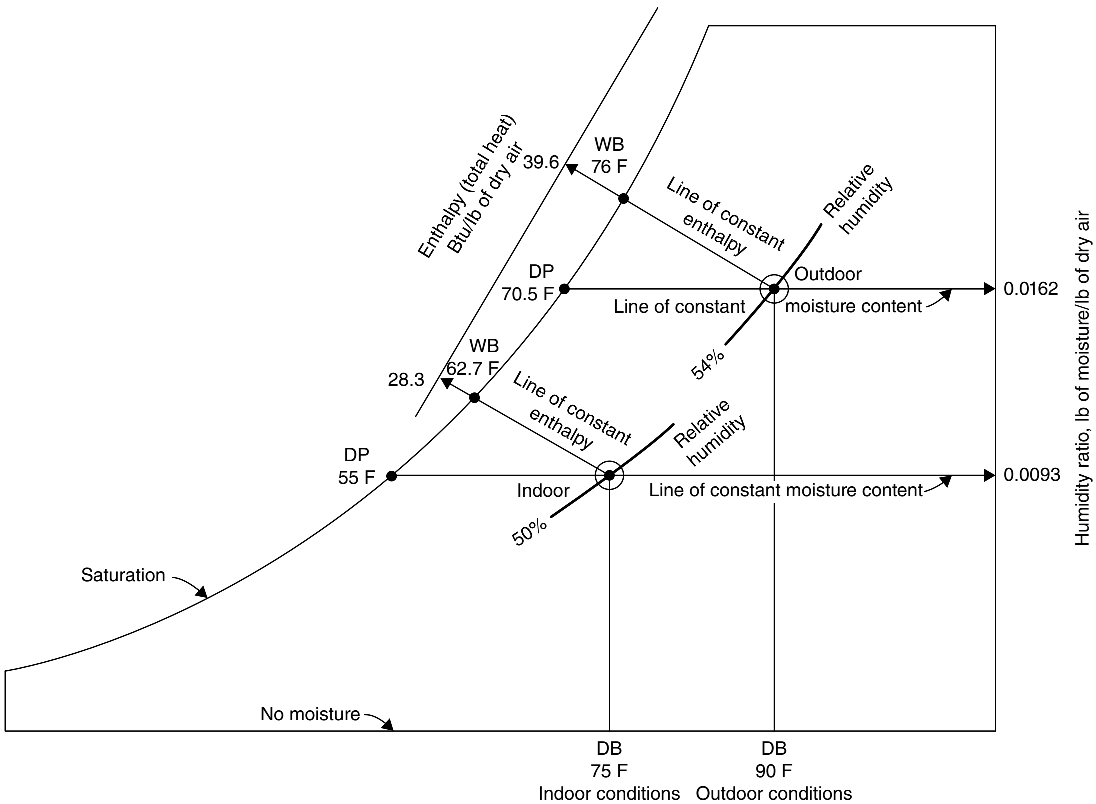


Fig. 12.2 *Use of the psychrometric chart to determine the change in enthalpy between given outdoor and indoor conditions.*

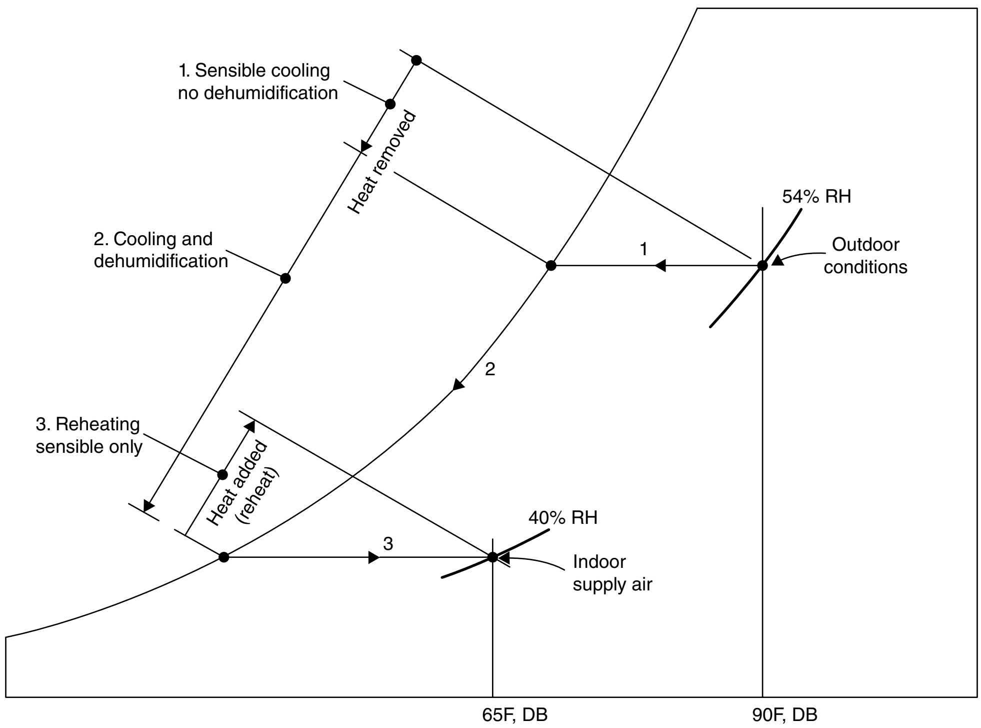


Fig. 12.3 *Process of cooling and dehumidifying outdoor air, summer conditions.*

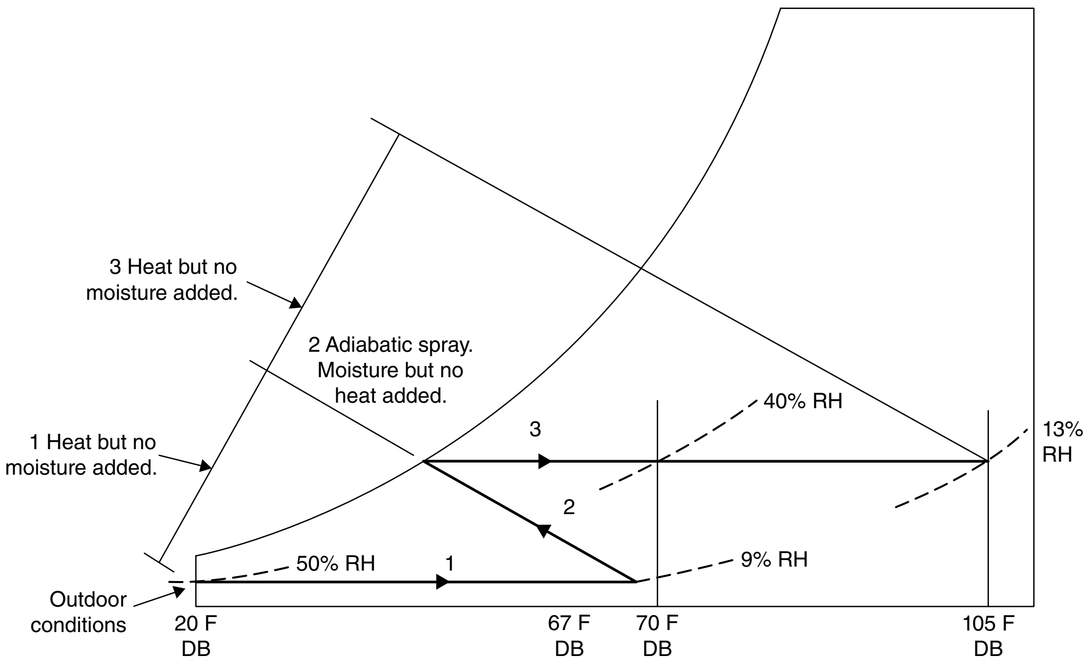


Fig. 12.4 *Process of heating and humidifying outdoor air, winter conditions.*

ratio so low that this moisture content would be unacceptably low when the outdoor air is warmed (step 1). Therefore, moisture must be added. Often this is accomplished through injection of a warm water spray. In Fig. 12.4, however, use of an adiabatic spray is illustrated—adiabatic meaning no change in enthalpy—in step 2. Then, in step 3, the saturated air is warmed to a higher temperature (105°F in this case) than the desired indoor conditions of 70 DB and 40% RH. This supply air then transfers its heat to the space. Note that this process starts at the desired indoor conditions and works backward (along step 3) to saturation, then downward along the constant enthalpy line (step 2) until reaching the line of constant humidity ratio of the warming outdoor air—in this case, 67°F DB. As with cooling, the changes in heat content can be read on the enthalpy scale.

(e) Metrics for HVAC System Performance

A wide variety of metrics (measures) for the expression of HVAC system and equipment performance will be encountered. In many cases there will be a mandated minimum performance threshold that is embedded in a building code. In the U.S., for example, minimum acceptable performance values for most common types of source equipment will be found in ASHRAE Standard 90.1. These values are usually the same minimum performance limits promulgated by the U.S. government. In almost all design situations, higher-performing equipment will be available from manufacturers. Such equipment will normally have a higher first cost than the code-minimum equipment—but the additional first cost may often be offset by energy savings and reduced life-cycle costs.

No matter the specific metric being considered, the performance of any given type of equipment will vary as its operating parameters vary. Listed equipment performance (and capacity) ratings are typically based upon a consensus standard that defines the parameters under which equipment will be rated. Such conditions are not necessarily the peak conditions that will be experienced in an actual building situation, so caution needs to be exercised when considering metrics such as efficiency or coefficient of performance (COP). In addition, most equipment operates less efficiently at partial load, and such reduced performance will affect annual energy consumption and payback analyses.

The following are some commonly encountered performance metrics that will affect HVAC system selection and design for buildings.

Efficiency, as discussed in Section 12.4(c), is the ratio of system output to system input when both values are presented in consistent units; it is expressed as a decimal value or percentage. Unless otherwise noted, efficiency should be taken to mean instantaneous efficiency at some defined point in time and under some specific set of operating conditions.

Annual fuel utilization efficiency (AFUE) is the ratio of annual fuel output energy to annual input energy, which includes any off-season pilot input loss.

Coefficient of performance (COP) is defined slightly differently, depending upon the task. For *cooling*, it is the ratio of the rate of heat removal to the rate of energy input in consistent units, for a complete cooling system (or factory-assembled equipment), as tested under a nationally recognized standard or designated operating conditions. For *heating* (heat pump), it is the ratio of the rate of heat delivered to the rate of energy input in consistent units, for a complete heat pump system as tested under designated operating conditions. Supplemental heat is not included in this definition.

Seasonal coefficient of performance for cooling or for heating (SCOPC, SCOPH) is the formulation of COP that considers the total output of a device during its normal operating season (versus an instantaneous output value for COP).

Energy efficiency ratio (EER) is the ratio of net equipment cooling capacity in Btu/h to the total rate of electric input in watts under designated operating conditions. (When consistent units are used, this ratio is the same as COP.)

Integrated part load value (IPLV) is a single-number figure of merit based on part-load EER or COP expressing part-load efficiency for air-conditioning and heat pump equipment on the basis of weighted operation at various load capacities for the equipment.

Seasonal energy efficiency ratio (SEER) is the total cooling output of an air conditioner during its normal annual usage period for cooling, in Btu, divided by the total electric energy input during the same period, in watt-hours.

Heating seasonal performance factor (HSPF) is the total heating output of a heat pump during its normal annual usage period for heating, in Btu, divided by the total electric energy input during the same period, in watt-hours.

Energy utilization index (EUI), also *energy use intensity*, is an indicator of total annual building energy usage normalized per unit floor area; Btu/ft^2 yr (W/m^2 yr); for a typical building, HVAC energy is a large part of EUI.

(f) Thermal Zoning

A thermal zone is an area of a building that must be provided with separate control if thermal comfort expectations are to be met. Thermal zones are very often a key basis for HVAC system selection, and zoning decisions can play a critical role in occupant comfort responses. Theoretically, the design team wants to provide just enough zones to meet the owner's project requirements (with perhaps some flexibility for anticipated future needs). Fewer zones will result in some level of discomfort. More zones than necessary will increase the first cost of the project.

Thermal zoning must be established prior to the selection of a climate control system. The concept of thermal zones applies equally well to passive climate control systems as to active climate control systems. A zone may be a room in a building, may consist of multiple rooms, or may be a portion of a room (a room may have more than one zone). The intent of zoning is to set up a control scenario that can respond to changing room loads and maintain thermally desirable conditions. Zone control in an HVAC system is most commonly initiated by a thermostat that senses room air temperature. As noted in Chapter 4, thermal comfort is affected by variables other than dry-bulb air temperature—nevertheless, temperature by itself is a de facto control variable in the vast majority of buildings. Successful zoning allows the HVAC control system to provide conditions amenable to thermal comfort in the face of changing heating and cooling loads. In a passive system, zone control might be exercised by opening and closing windows or draperies.

Thermal zoning decisions are typically driven by differences in the timing of loads from one room to another. Timing (scheduling) is the driver—not differences in the magnitude of loads. As an example, an east-facing office must be zoned separately from a west-facing office due to solar radiation patterns. If the two offices are on the same zone (with one thermostat), the occupants of the office without a thermostat (without control capability) will be consistently uncomfortable. The same would be true of a classroom placed on the same zone as an office. If the thermostat is in the office, the system cannot respond to changes in classroom occupancy (empty, half-full, full).

To repeat, thermal zoning must precede system selection—so that a system with adequate zoning capability for the project context is selected. The minimum number of thermal zones for a conventionally designed multipurpose, mid-rise building is shown in Fig. 12.5. More than the minimum 16 zones could be required due to differences in load scheduling within a zone, such as between offices and stores or between offices and conference rooms. The apartments are also shown with the minimum five zones (based on solar orientation); an emphasis, however, on individual ownership of units and the variation in usage patterns typical of residential

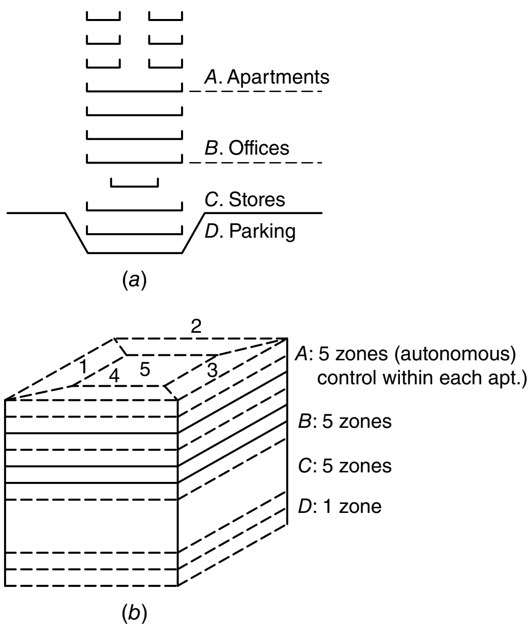


Fig. 12.5 *A reasonable minimum number of thermal zones for a large multipurpose building.*

occupancies often results in a decision to provide as many zones as there are apartment units. Otherwise, the hard decision of which apartment gets a thermostat and which does not will need to be addressed.

It may be premature to call it a trend, but there seems to be a lot of interest in Europe in personal control systems for ventilation and thermal comfort. Under this approach, each workstation is set up as a separate thermal zone whose conditions are controlled by the occupant. This approach is logical; although likely expensive—not just for the control capability, but also for the distribution delivery elements. There are also limits upon building types where this would make sense (each classroom seat in a school would be hard to individually zone). On the other hand, comfort, energy efficiency (perhaps), and diversity of conditions would be fostered when this zoning arrangement is possible.

Once the basics of system zone determination have been established, a design philosophy question is in order. How similar should the interior environments of buildings be? This question encompasses not only thermal experiences, but visual and acoustical ones as well.

The advantages of uniformity are most evident in ease of design and construction that, through mass production and speed, often brings lower first costs. In the case of an office, uniformity of ceiling heights, light fixture placement, grille locations, and so on promotes flexibility in varying arrangements that can extend a building's usable life span. There are, however, at least four types of offices that may need to be interchangeable within such generic space. The typical *enclosed office* has the privacy of four walls and a door. The *bullpen office* has repeated, identical workstations, with low dividers at about the height of the desk surface. The *uniform open-plan office* resembles the bullpen, but with higher divider partitions for added privacy. The *free-form open-plan office* has some individually designed workstations with divider partitions of varying heights (sometimes reflecting the varying status of workers). In the bullpen and uniform open-plan office, the resulting uniformity is not always attractive to users, and diversity is often encouraged at a more personal level—with office furnishings, for example. A more thorough approach to diversity can provide stimulus to the user who spends many hours away from the variability of the exterior climate.

If offices must be uniform with respect to ceilings, lighting, air distribution, and even size, the corridors that connect them and the lounges or other supporting service spaces can deliberately be made different. Diversity requires a complete and detailed design of places; it gives the builder a more complex and interesting task; and it can provide orientation and interest to the users. The attractiveness of diversity is evident in most collections of retail shops, in which light and sound—and sometimes heat and aroma—are used to distinguish one shop from the next.

Diversity in the thermal conditions to be maintained, such as warmer offices and cooler circulation spaces in the winter, can be used to enhance the comfort of the office users. Designers have long recognized that a space can be made to seem brighter and higher if it is preceded by a dark, low transition space. Thermal comfort impressions can be manipulated similarly. Less than comfortable conditions in circulation spaces or other less-critical zones not only make the key functional spaces seem more comfortable by contrast, but also save significant amounts of energy over the life of a building. Furthermore, allowing diversity in conditions can make passive strategies more feasible.

A large-scale demonstration of diversity in thermal zones is shown in Fig. 12.6. Passive solar heating can make a significant contribution, even through a shallow-sloped, single-glazed cover in cloudy Glasgow, Scotland, largely because the mall area and leisure areas are allowed a much wider thermal range than would be permitted in stores and offices. The overcast skies are quite suitable for daylight, and the addition of summer sunshading makes natural ventilation (through the stack effect, assisted by fans) possible during the cool summers. U.S. Pacific Northwest climate conditions are similar.

(g) Preliminary Space Requirements for HVAC

Detailed information regarding the floor area and distribution volume requirements for an HVAC system will become available during the design development phase of a project. Unfortunately, architectural design decisions regarding these space requirements were made much earlier—probably during the conceptual design phase as floor plans were first

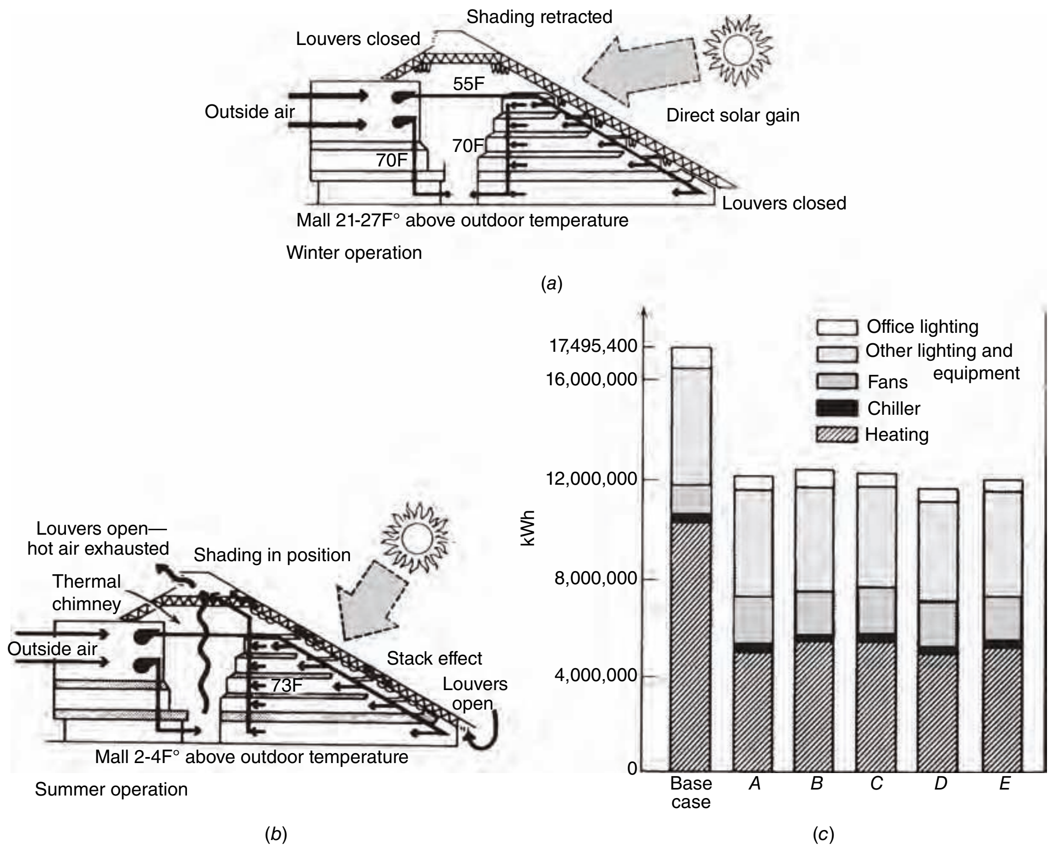
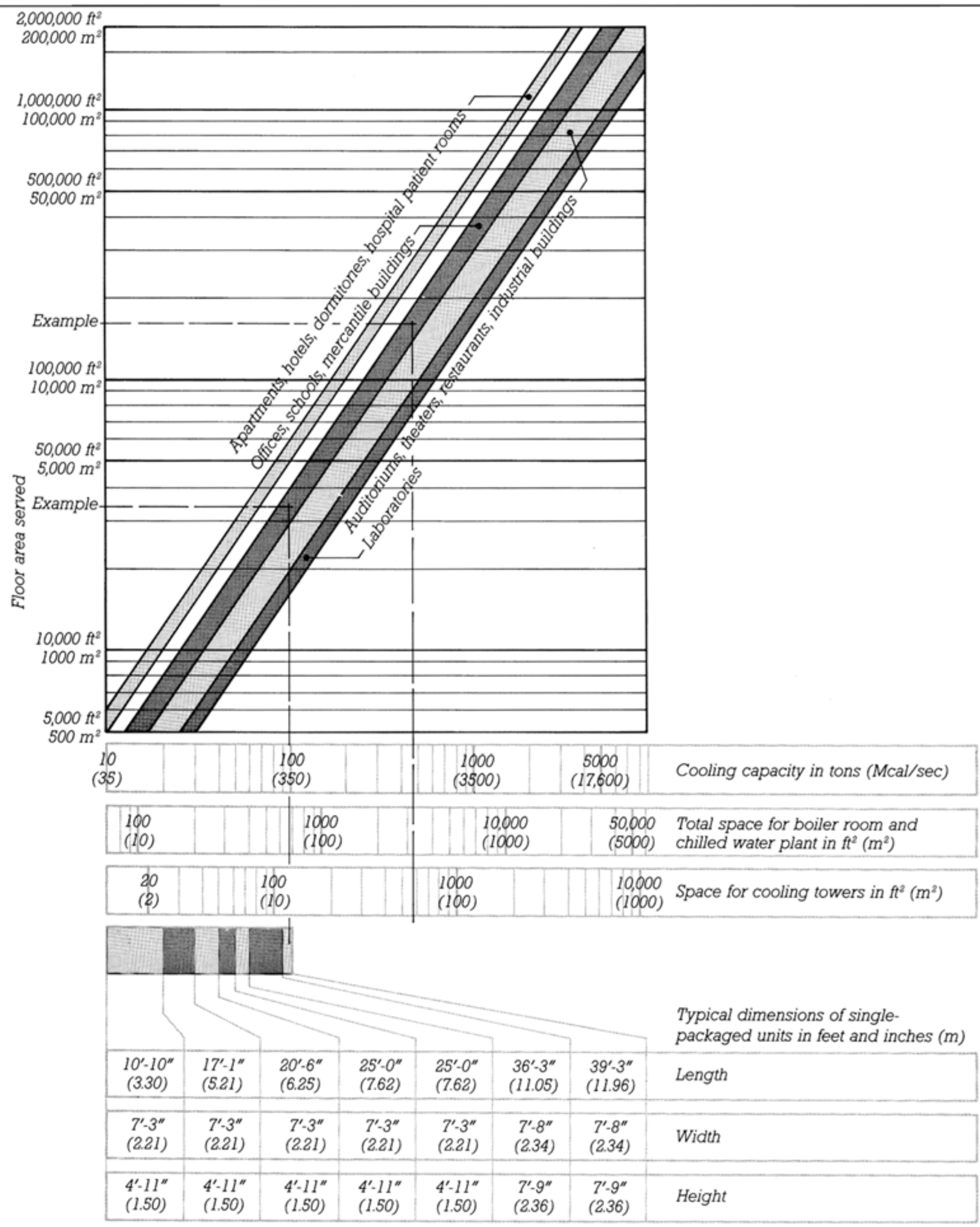


Fig. 12.6 *St. Enoch's Square, Glasgow, Scotland: a proposal to use passive solar heating, daylighting, and natural ventilation. Reiach & Hall and GMW Partnership, architects (joint venture); Cosentini Associates, energy consultants; Princeton Energy Group, daylighting consultants. (a) Schematic section showing winter operation; the mall temperature varies around 63°F (17°C) during operating hours, while offices are kept near 70°F (21°C). (b) Schematic section showing summer operation; the mall temperature varies from about 68 to 74°F (20 to 23°C) during operating hours. (c) Estimates of annual energy consumption for a conventional-design base case and several alternative configurations. Note the significantly lower heating energy requirements, resulting in part from the lower winter temperatures allowed for the less-critical zones such as the mall and the leisure areas in configurations* A *to* E.

developed and accepted by the owner. Providing too much space for HVAC artifacts is not architecturally desirable, but a boon to the HVAC designer. Providing too little space for HVAC equipment, distribution, and maintenance is a serious problem that will likely compromise system performance and longevity. Having HVAC expertise available to the design team early in the design process can go a long way toward right-sizing space allocations. This can be accomplished through an integrated design process or (somewhat less so) via a well-implemented commissioning process. In the absence of such early expertise, precedent buildings can be used to inform space decisions; or, a design guidance tool (such as seen in Figs. 12.7 or 12.8) can be employed.

There is no single correct HVAC system for most building types, no single correct way to arrange an HVAC system, and no single correct way to place the system into a building. Fortunately, many decisions that need to be made to properly integrate an HVAC system into a building are contextual, rather than technical, issues. The project architect usually knows more about project context than any other design team member. Some of the issues to be considered early in the HVAC placement process are whether the system will be a local (requiring no central space allocation), central, or district (where source equipment is remote from the building) system and what the most logical distribution of major equipment might be.



Example: Find approximate sizes for all-air system in a 150,000-ft² department store:

Cooling capacity: about 450 tons

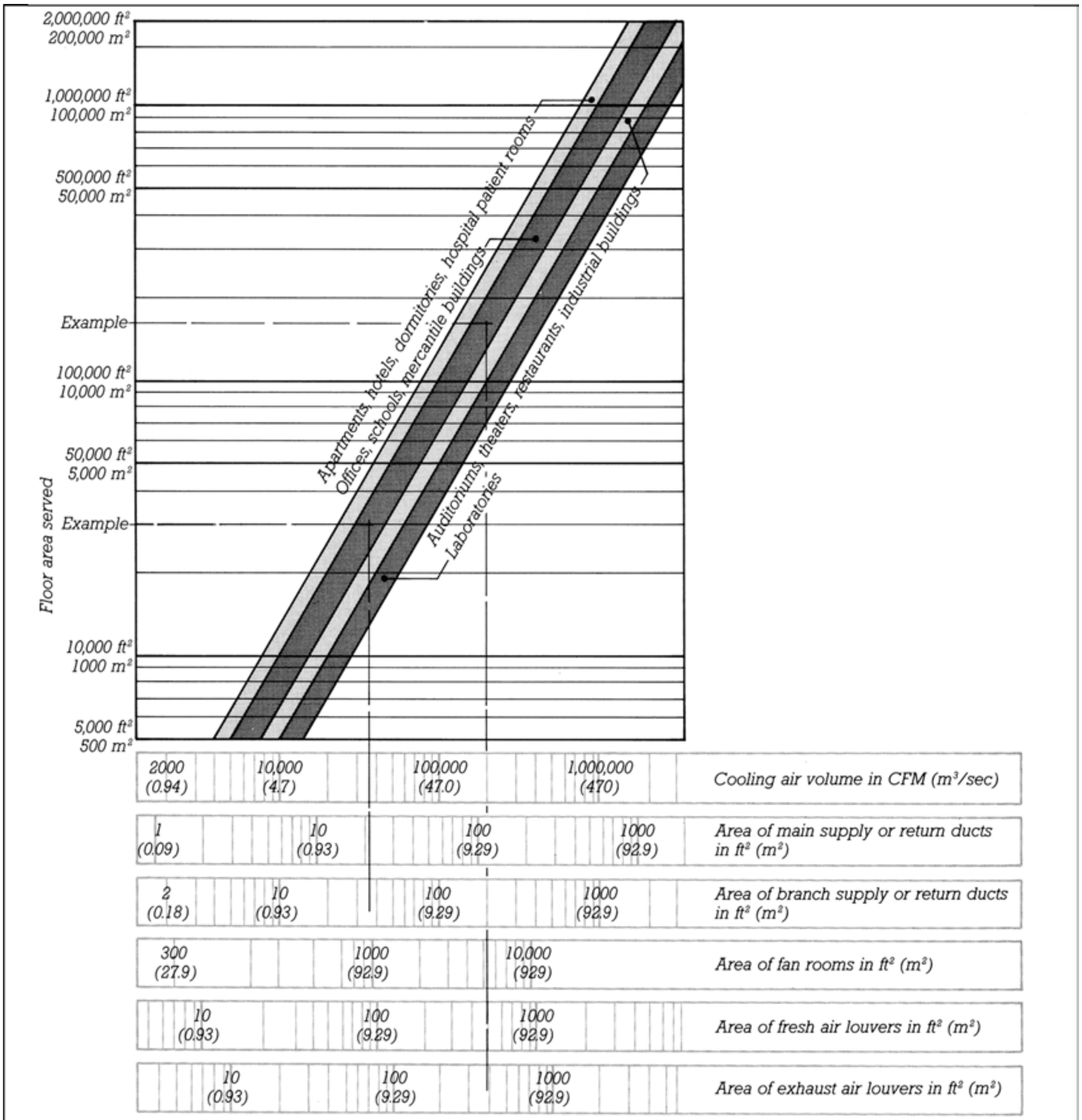
Total space boiler/chiller room: about 3200 ft²

Cooling towers: about 560 ft² of roof area (or other outdoor space)

Packaged unit sizes: no single unit large enough; largest such unit (39 ft 3 in. × 7 ft 8 in. × 7 ft 9 in.) serves about 33,000 ft² of this building, so five such units could be arranged on rooftop, to meet total load.

Fig. 12.7 *Approximate space requirements for major heating and cooling equipment.*

Source: Reprinted by permission from Edward Allen and Joseph Iano, The Architect's Studio Companion, *5th ed. © 2011 by John Wiley & Sons, Inc.*



Example: Find approximate sizes for all-air system in a 150,000-ft² department store:

Central fan: moves a volume of about 220,000 cfm

Main supply/return ducts: each, 120 ft² total cross-sectional area

Branch supply/return ducts: each, 300 ft² total cross-sectional area

Fan rooms: 5200 ft² total area

Fresh air louvers: 500 ft² total area

Exhaust air louvers: 400 ft² total area

If rooftop packaged units are used, each unit needs both supply and return main duct area of about 21 ft²; and both supply and return branch duct area of about 35 ft².

Fig. 12.8 *Approximate space requirements for air-handling equipment.*
Source: Reprinted by permission from Edward Allen and Joseph Iano, The Architect's Studio Companion, *5th ed. © 2011 by John Wiley & Sons, Inc.*

An important decision is whether to spatially group or separate the HVAC *source* equipment and the HVAC *distribution* (air-handling) equipment (see Fig. 12.61). A single central mechanical room in a good location might serve an entire building, with area and height sufficient for both heating/cooling and air-handling equipment. If separated, a large space for heating/cooling equipment is typically located in the basement or the penthouse, with a fan room on each floor (or alternate floors).

A central mechanical (plant, source equipment) room should be located so as to: minimize distribution component runs to fan rooms, minimize electrical distribution runs from the building service, allow for easy installation and replacement of large and heavy equipment, allow for easy connection to cooling towers/air-cooled condensers, simplify noise control, minimize structural systems costs, and (as necessary) simplify provision of fuel storage. Mechanical rooms need relatively high ceilings; 12 ft (3.7 m) clear is a typical minimum.

A fan room should be logically located relative to the areas being served and have easy access to the exterior for connection to an outdoor air intake. Central locations minimize the distribution tree size and length (100 ft [30 m] might be considered a maximum run for energy efficiency); access to the exterior facilitates the use of outdoor air for both IAQ and economizer cycle purposes and simplifies equipment installation (or removal during remodeling). Fan rooms do not require the same ceiling height as a central mechanical room; 10 ft (3.1 m) clear is often acceptable—although getting ductwork into and out of the room may be as volumetrically demanding as placing the air-handling unit. Although air-handling units are typically not nearly as noisy as chillers, placement of a fan room to facilitate ductborne noise control makes economic sense.

Figures 12.7 and 12.8 present approximate space requirements for conventional mechanical systems. For more detailed information on equipment room space requirements, see Figs. 12.12, 12.30, and 12.36.

The charts presented in Figs. 12.7 and 12.8 are intended to give a quick approximation of areas; more detailed procedures for sizing boilers, chillers, fan rooms, and air ducts are presented later in this chapter. The width of the diagonal "line" drawn to represent each building type in Figs. 12.7 and 12.8 allows some opportunity for consideration of building energy efficiency. An efficient building will fall toward the left of a given building-type-line width. These preliminary estimates for equipment sizes are likely excessive for a substantially high-performance building (such as one based upon the recommendations in the ASHRAE *Advanced Energy Design Guides*). For buildings with large heat gains or losses, however, these graphs may slightly undersize the areas needed.

EXAMPLE 12.2 Estimate the central equipment room floor space needed to serve the Oregon office building shown in Fig. 12.2. The total floor area of this office building is 24,000 ft^2 (2230 m^2).

SOLUTION

Enter Fig. 12.7, space for major equipment, considering an office building floor area of 24,000 ft^2. Space for the boiler and chiller is estimated at about 500 ft^2. Enter Fig. 12.8, space for air handling, for a 24,000 ft^2 office building. Space for the fan room is estimated at about 800 ft^2. Thus, a central mechanical room (with boiler, chiller, and air-handling unit) is estimated to require 500 + 800 = 1300 ft^2 (121 m^2). The actual size of the mechanical room in this real building is 1200 ft^2, a very close prediction.

Now, approximate the largest duct sizes. There are five bays on the building's upper floor, each at 1440 ft^2, for a total of 7200 ft^2 (669 m^2). The building's mechanical room is located beyond the east end of this floor, so all the supply air must enter through one end of the central duct. Figure 12.8 indicates the following for an office building at 7200 ft^2:

Volume of air: 7000 to 11,000 cfm
Area, main supply or return ducts: 4.0 to 6.5 ft^2

The actual main supply duct size for this floor is 2.6 ft^2. The chart thus overestimated the duct size by about 50% for this energy-efficient (well-insulated, shaded, and daylit) building. ■

The capacity of cooling equipment is commonly rated in tons of refrigeration. Rough estimates of cooling capacity versus floor area for several building types are provided in Table 12.1.

For a thermally well-designed detached *residence*, a design guideline of 1000 ft^2 of floor area/ton (26 m^2/kW) is suggested.

TABLE 12.1 Preliminary Estimates for Cooling Capacity

	Floor Area Served		
Type of Occupancy	**ft^2/ton**	**m^2/ton**	**Assumptions**
General occupancy:	350–550	32.5–51	400 cfm/ton (189 L/s per ton)
Perimeter spaces			1.5 cfm/ft^2 (0.7 L/s per m^2)
Interior spaces			0.6 cfm/ft^2 (0.3 L/s per m^2)
Offices	500	46.5	200 ft^2/person (18.6 m^2/person) 3.5 W/ft^2 (38 W/m^2) for lights, equipment
High-rise apartments			
North-facing	1000	93	
Other orientations	500	46.5	
Hospitals	333	31	1000 ft^2/bed (93 m^2/bed)
Shopping centers	400	37	
Department stores			2 W/ft^2 (21.5 W/m^2)
Specialty stores			5 W/ft^2 (53.8 W/m^2)
Hotels	350	32.5	
Restaurants	150	14	
Central plants			
Urban districts	380	35.5	
College campuses	320	29.5	
Commercial centers	475	44	
Residential centers	500	46.5	

Source: Grondzik (2007).

Note: 1 ton = 12,000 Btu/h (3.514 kW).

HVAC COMPONENTS

An HVAC system is composed of a number of components (Fig. 12.9)—each with a specific function. Because of the potential complexity of many common HVAC arrangements, looking at conceptual building blocks for these systems may assist in demystifying the options. Each of these categories of components will be looked at in turn prior to exploring the numerous HVAC systems that may be considered for building applications. Four main categories of functional elements will be encountered in the typical HVAC system:

Source components. These produce heating effect and/or cooling effect.

Distribution components. These circulate the heating/cooling effects from the source(s) to the various conditioned zones (in a local system this component category is minor or nonexistent).

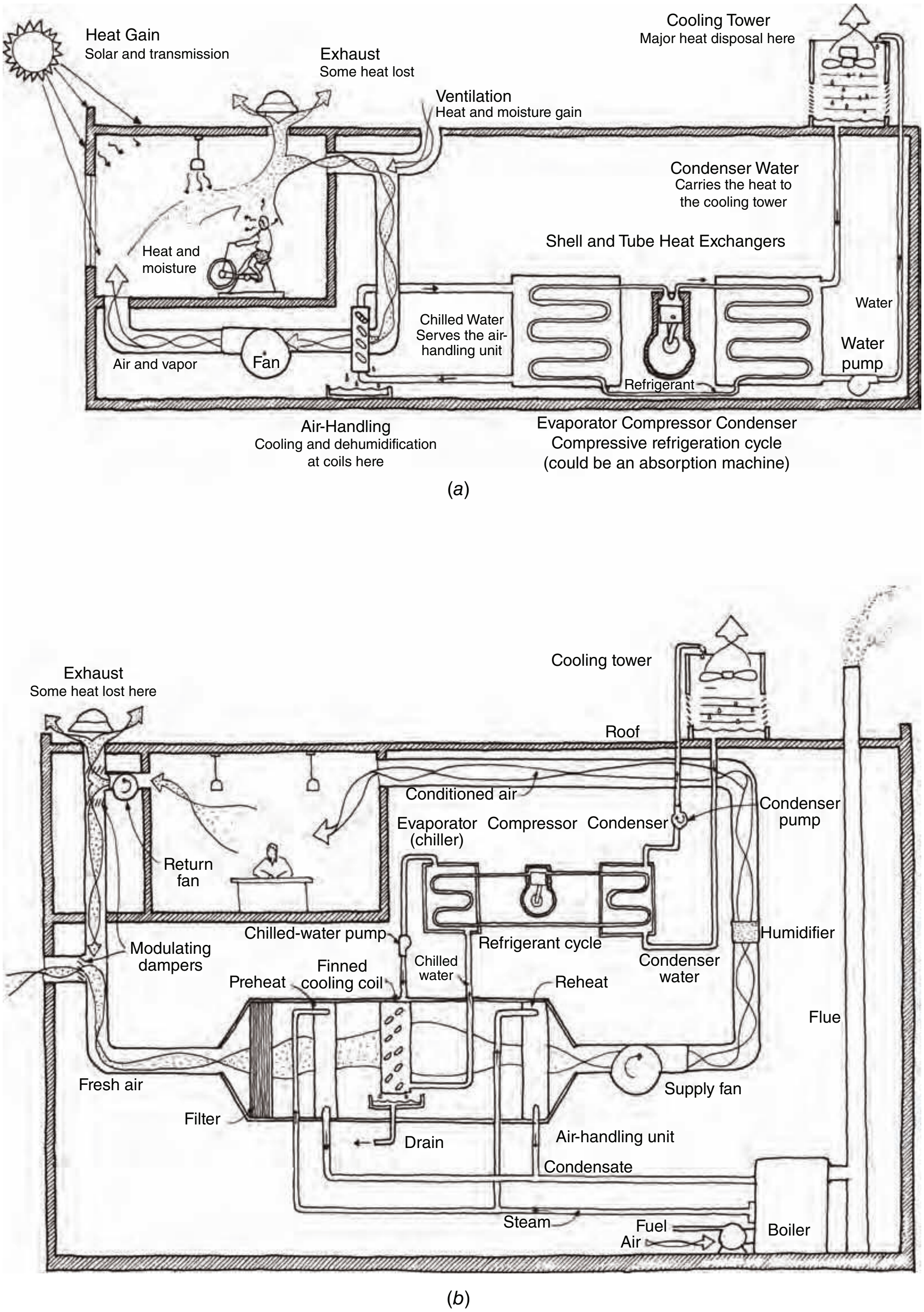
Delivery components. These introduce the heating/cooling effect into the various spaces being conditioned.

Control components. These provide for beneficial operation of a system, such as on-off functionality, temperature control, energy efficiency, freeze protection, fire response, etc.

12.5 SOURCE COMPONENTS: HEAT

An HVAC system that will offset building heat losses must have a heat source. Selection of a heat source is a high-level decision that should generate some design reflection. There are four conceptually (and physically) different means of introducing heat into a building. They have different architectural design impacts and environmental concerns/benefits. The four basic approaches mushroom into dozens of specific equipment options—and these options expand into more dozens of specific equipment offerings.

On-site combustion: A fuel of some type (natural gas, oil, propane, firewood, coal) is burned on site, usually within the building; heat is produced as an outcome of the combustion process. The fuel may be delivered to the building site upon demand (natural gas) or be delivered in bulk for on-site storage (fuel oil). Combustion air will need to be provided



Interactive Animation

Fig. 12.9 *Some basic components of HVAC central equipment. (a) A simplified diagram of a cooling cycle, in which chilled water is circulated to air-handling coils, and heat is disposed of through a cooling tower. (b) Schematic diagram of major components of central equipment for both heating and cooling.*

at the combustion location and combustion gases exhausted from the building. With the exception of biomass, heating fuels are nonrenewable and all produce carbon emissions. Efficiencies of combustion equipment can vary substantially, but modern equipment (such as a condensing boiler or furnace) tends to perform at or above 95% efficiency. Hot water or hot air can be produced by combustion sources.

Electric resistance: Electricity is passed through an electrical resistance element to produce heat; the electricity may come from an off-site (via a utility) or on-site source (such as PV or wind). Electric resistance heating is typically cited as being 100% efficient—but this is a site efficiency (similar to the 95%+ value noted for on-site combustion). Electricity is generally delivered to a building on demand (with storage only required for some approaches to on-site generation). No combustion air or exhaust for products of combustion is necessary. Hot air or hot water can be produced by electric resistance. The distinction between site and source efficiency is of particular interest for electric resistance (typically involving a 1:3 magnitude ratio).

Heat transfer: Finding some heat already on site and moving this heat to a place where it is more useful is the essence of heat transfer. An air-to-air heat exchanger (whereby heat in exhaust air is transferred to incoming fresh air) is an example of this approach; a heat pump (discussed in more detail in Section 12.8*e*) is another example of this approach. A heat-transfer system may use electricity as a driving force or be self-powered. Heat transfer does not require the introduction of "new" energy and can be very energy effective; ground-source heat pump COPs can reach 5–6, and air-source units should be greater than 1.5 (denoting more than 100% "efficiency"). Heat pumps and air-to-air heat exchangers are both commonly found in high-performance buildings. In general, hot water or hot air may be produced—but this choice is limited by the specific transfer equipment being considered

Energy capture: This approach is similar to heat transfer, but an energy form other than heat is tapped into and converted to heat for use in a building. Solar energy is by far the most common such energy resource (although wind is also covered by this approach). Energy capture sources tend to be carbon-free and also economically free for the taking. Hot water or hot air may be readily produced.

12.6 HEATING EQUIPMENT

Several examples of heat source equipment and applications are provided by way of introduction to this important part of an HVAC system.

(a) Boilers

Boilers produce hot water or steam; the heat source may be electric resistance or on-site combustion. Boilers provide the heating effect required to elevate water temperature to a point where it can be used for building heating (or to evaporate water to steam). There are a number of different types of boilers on the market—attesting to a wide range of application contexts and system demands. The type of boiler selected for a project depends upon the size of the building heating load, the heating fuels available (and desired), the desired efficiency of operation, and whether single or modular boilers are the most reasonable. Boiler sizes are commonly expressed either in Btu/h (kW) of net output or in (gross) boiler horsepower.

In I-P units,

$$\text{boiler horsepower} = \frac{\text{heating load (Btu/h)}}{\text{\% boiler efficiency}} \times 33{,}470 \text{ Btu/h per horsepower}$$

In SI units,

$$\text{boiler horsepower} = \frac{\text{heating load (kW)}}{\text{\% boiler efficiency}} \times 9.81 \text{ kW per horsepower}$$

Efficiency depends partly on the number of passes that the hot gases (from on-site combustion) make through the water—the more passes, the higher the efficiency. It also depends on burner efficiency and on regular maintenance. Finally, efficiency is highest when boiler equipment is operating near its capacity. Fig. 12.10 compares typical boiler types, including two- and three-pass boilers.

Fire tube boilers: The hot gases of the fire are taken through tubes that are surrounded by the water to be heated. Fire tube boilers can be either dryback or wetback. Dryback designs have chambers outside the vessel to take combustion gases from the furnace to the tank. Wetback designs have water-cooled chambers that conduct the

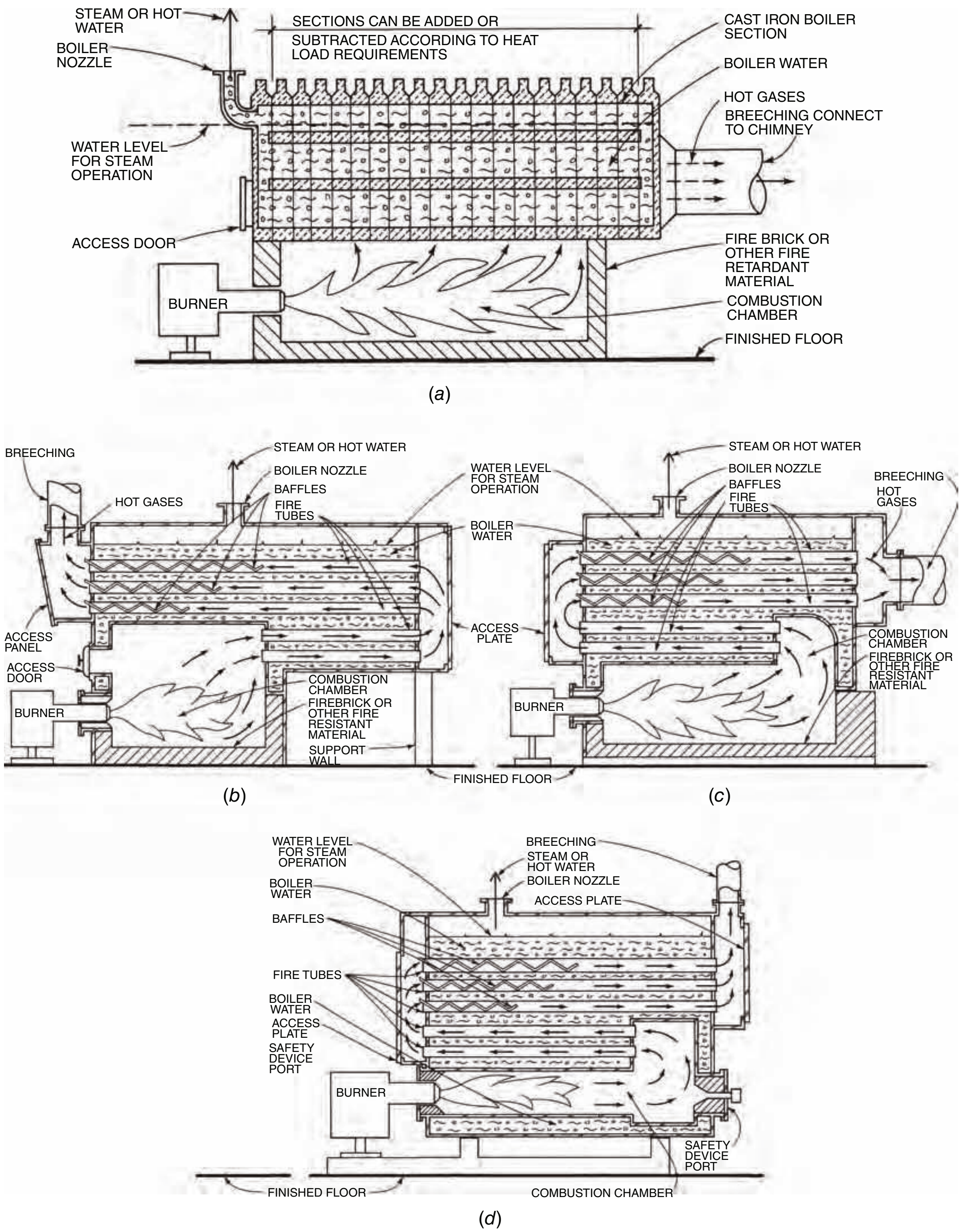


Fig. 12.10 *Comparison of boiler types. (a) Cast-iron sectional type. (b) Two-pass fire tube. (c) Three-pass fire tube. (d) Three-pass wetback Scotch marine. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *9th ed.; © 1994 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

combustion gases. Firebox boilers place the boiler shell on top of the combustion chamber. Scotch marine boilers feature multiple passes of the combustion gas through tubes.

Water tube boilers: The water to be heated is taken through tubes that are surrounded by the boiler's fire. They hold less water than the fire tube models and so respond faster and can generate steam (where desired) at higher pressures.

Cast-iron boilers: Often used in residential and light-commercial applications, these boilers operate at lower pressure and lower efficiency. They do have the advantage of being modular.

In addition to basic boiler construction, there are choices for burner types (depending on the fuel used), burner controls, and boiler feedwater systems. See Chapter 32 in the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* for details.

(b) Boiler Installation Considerations

Fuel-burning boilers need flues for exhaust gases, fresh air for combustion, and have mandatory air pollution control equipment and controls. The exhaust gas is usually first taken *horizontally* from the boiler; this horizontal enclosure, or flue, is called the *breeching*. The *vertical* flue section is called the *stack*. Guidelines for sizes and arrangements of breeching and stacks are shown in Fig. 12.11. Local codes determine the quantity of air required for combustion; local or national air pollution authorities set pollution control requirements. As a general rule, combustion air can be supplied through a duct to the boiler at an average velocity of 1000 fpm (5.1 m/s). The duct should be large enough to carry at least 2 cfm (1 L/s) per boiler horsepower. Furthermore, ventilation air to the boiler room should be provided; preferably, the inlet and outlet should be on opposite sides of the room. Minimum sizes: enough for 2 cfm (1 L/s) per boiler horsepower at a velocity of about 500 fpm (2.5 m/s).

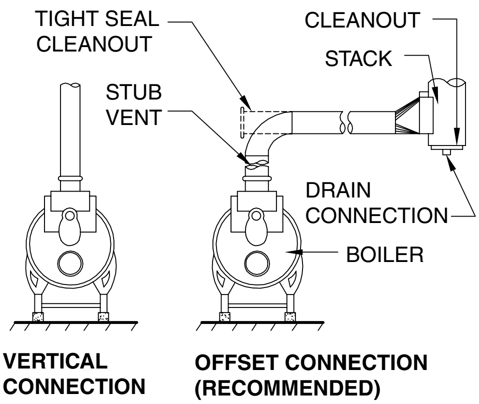
Electric boilers may be used when and where electricity costs are competitive with the cost of combustion fuels. Both hot water and steam electric boilers are available. The advantage of electric boilers is the elimination of a need for combustion air, a flue, and air pollution mitigation at the building site. The disadvantages are the use of a high-grade energy source for a relatively low-grade task and the pollution impact at the electric generating plant. In order to reduce the possibility of high electric demand charges, a large number of control steps may be desirable.

Space requirements and arrangements for boilers are summarized in Fig. 12.12, which is predicated on multiple boilers. Note that clear space within the room must be provided so that the tubes of the boiler can be pulled out when they must be replaced. A viable strategy for eventually replacing an aging boiler must be considered, and adequate access provided.

When space demands are a vexing design consideration, smaller-dimension boilers—*compact boilers* (Fig. 12.13)—with high thermal efficiencies are available. In addition to their space-saving footprint, these boilers feature a variety of venting options that make them easily adaptable to smaller equipment rooms.

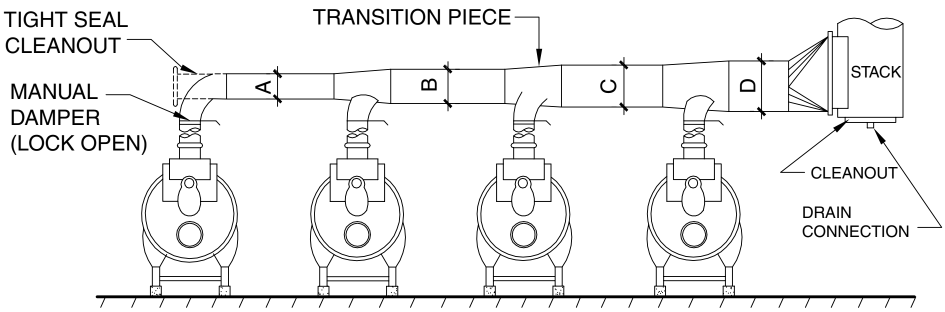
Two other types of boilers are discussed in the following material—steam boilers and modular boilers. Modular boilers are often preferred for energy conservation. Steam boilers are used, as may be apparent, to produce steam. Steam was very commonly used as a heat-transfer medium in older buildings and is still used for district heating systems. The main rationale for steam climate control systems is the high thermal capacity of steam (changing the state of a substance is an effective way to embody energy in a fixed mass of substance). Steam systems, however, require greater attention to safety and maintenance than hot water systems—and appear to be on the decline as an option of choice for single-building systems. Steam may still be encountered for space-heating purposes, and is still necessary in some building types for tasks such as sterilization.

High-output, package-type steel boiler: One or several such boilers may be installed in a large building that uses steam as a primary heating medium. Direct use of steam for climate control can be seen in Fig. 12.9*b*, supplying preheat and reheat coils and also a humidifying unit. The relative lightness of this boiler type, compared to the older styles with heavy masonry bases (boiler settings), makes it suitable for use on an upper floor of a tall building. Figure 12.64 shows two such boilers on the 13th floor of the Fox Plaza Building.



STACK DIAMETER–MULTIPLE BOILERS, COMMON BREECHING AND STACK

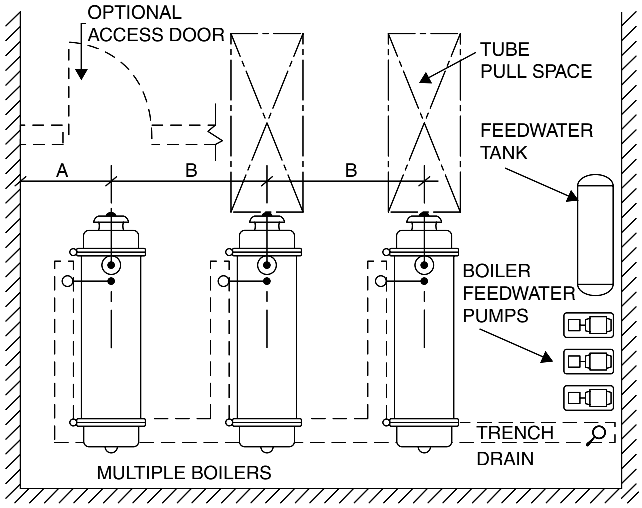
MINIMUM STACK DIAMETER (IN.)						
NO. OF BOILERS	2		3		4	
LENGTH OF STACK	100′	200′	100′	200′	100′	200′
BOILER HORSEPOWER						
25–40	11	12	13	14	14	16
50–60	13	14	15	16	17	18
70–100	16	17	19	20	21	23
125–200	21	22	24	26	28	30
250–350	26	28	32	34	34	40
400–600	32	34	38	40	42	46



MULTIPLE BOILERS WITH COMMON BREECHING

MINIMUM BREECHING DIAMETER (IN.)				
NUMBER OF BOILERS	1	2	3	4
BOILER HORSE POWER	A	B	C	D
15–20	6	8	9	9
25–40	8	10	11	12
50–60	10	12	14	15
70–100	12	15	17	18
125–200	16	20	22	24
250–350	20	25	28	30
400–600	24	30	33	36
700–800	24	34	38	42

Fig. 12.11 *Breeching and stack size guidelines for fossil-fuel-fired boilers. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*



BOILER ROOM SPACE REQUIREMENTS

BOILER HP	15–40	50–100	125–200	250–350	400–800
Dimension A	5′–9″	6′–6″	6′–10″	7′–9″	8′–6″
Dimension B	7′–5″	8′–9″	9′–7″	11′–9″	14′–3″

Fig. 12.12 *Boiler room space requirements. Dimension A includes an aisle of 3 ft 6 in. (1 m) between the boiler and the wall. Dimension B between the boilers includes an aisle of at least 3 ft 6 in. (1 m), up to 5 ft (1.5 m) for the largest boilers. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 10th ed.; © 2000 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

A building that uses primary steam boilers or receives steam from a district heating system may have secondary hot water distribution circuits. In such a situation, a steam to hot water converter (Fig. 12.14) is used as a heat exchanger. In the system shown in Fig. 12.64, there is a downfeed steam supply from the two boilers on the 13th floor to two such converters, one for hot water heating in the apartments and one below the garage ceiling for hot water heating in the commercial area. A converter may also be used to transfer heat from steam to *domestic* (potable) water.

Modular boilers: The primary advantage of modular boilers (Fig. 12.15) is efficiency. Boilers achieve maximum efficiency when they are operated continuously at their full-rated fuel input. Large-capacity boilers operate this way only under design conditions, which by definition occur, at most, 5% of the time during a normal winter. Most of the time, large boilers in building applications are running at part load and reduced efficiency. In a modular boiler design, each boiler section is run independently. Therefore, only one section need be fired for the mildest heating needs; as the weather gets colder, more sections are gradually added. Because each section operates continuously at full-rated fuel input, efficiency is greatly increased (Fig. 12.16). Each module, being rather small, requires little time to reach a useful temperature and (unlike a larger single boiler) does not waste a lot of heat as it cools down. Thus, modular boilers usually produce a 15% to 20% fuel savings for the heating season relative to single boilers. Their other advantages include ease of maintenance (one module can be cleaned while others carry the heating load) and small size (allowing for easy installation and replacement in existing buildings).

Modular boilers also eliminate the initial cost of oversizing heating equipment. In cold climates, conventional boiler systems often use two or three large boilers to ensure that heat is available if one boiler fails. When two such boilers are used, it is common practice to size each boiler at two-thirds

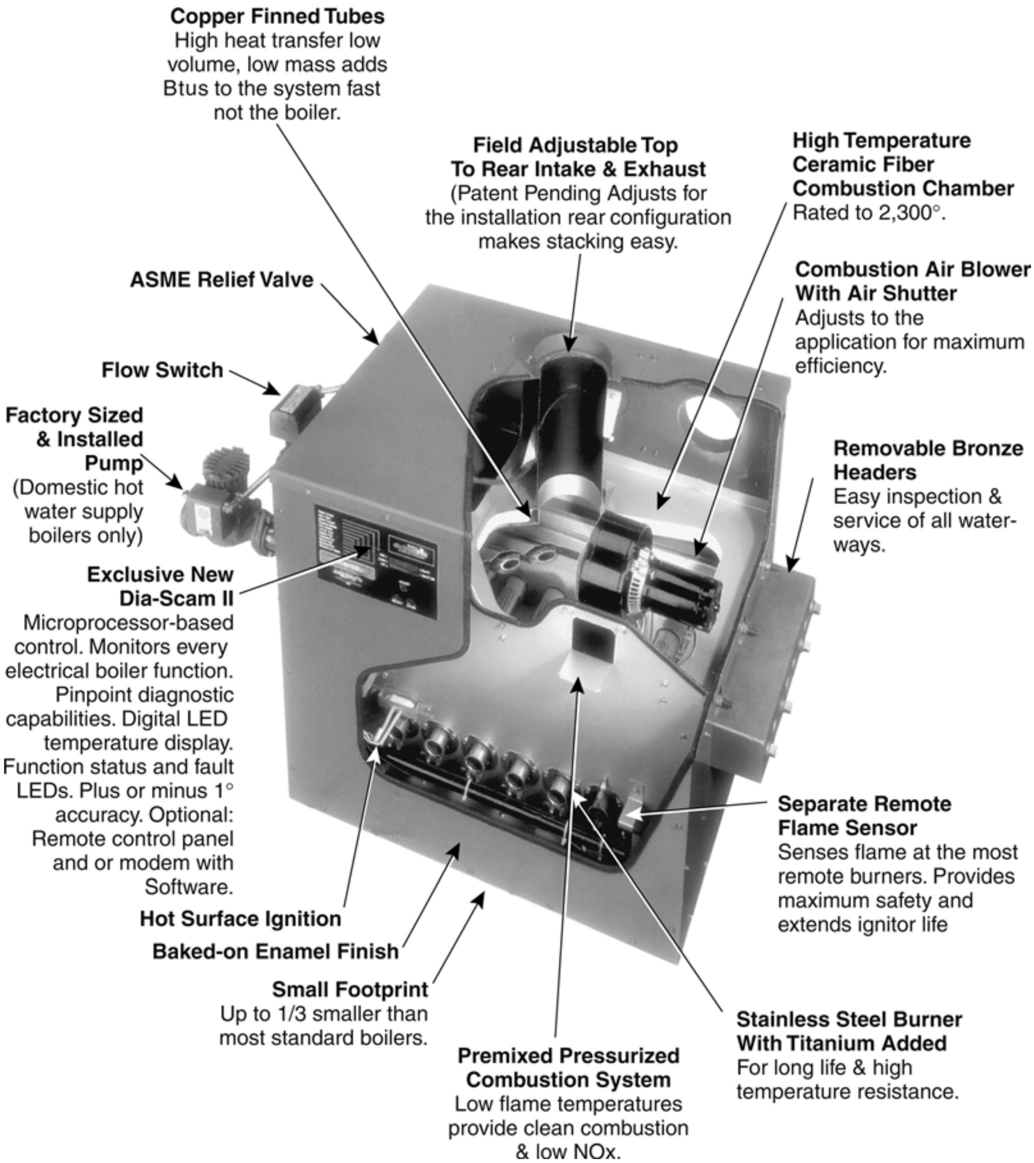


Fig. 12.13 *Burkay Genesis hot water boiler, fueled by either natural gas or propane, is available in ratings from 200,000 to 750,000 Btu/h (58,620 to 219,825 W). All units are 30 in. high × 24 in. deep (762 mm × 610 mm); the smallest boiler is 23 in. (584 mm) wide, and the largest is 57 in. (1454 mm) wide. The copper heat exchanger has an 83.7% thermal efficiency rating, and a variety of venting options are available. (Courtesy of A.O. Smith Water Products Company, Irving, TX.)*

of the total heating load; an oversize of one-third results. When three such boilers are used, it is common practice to size each boiler at 40% of the total heating load; an oversize of 20% results. However, when at least five modular boilers are used, oversizing can be eliminated because the failure of a single module will not have a crippling impact on the overall heat output.

Gas-fired pulse boilers are a smaller and more energy-efficient choice for modular boilers. Pulse boilers utilize a series of 60 to 70 small explosions per second, making the hot flue gases pulse as they pass through the fire tube. This makes for very efficient heat transfer. Pulse boilers are available up to about 300,000 Btu/h (88 kW) capacity.

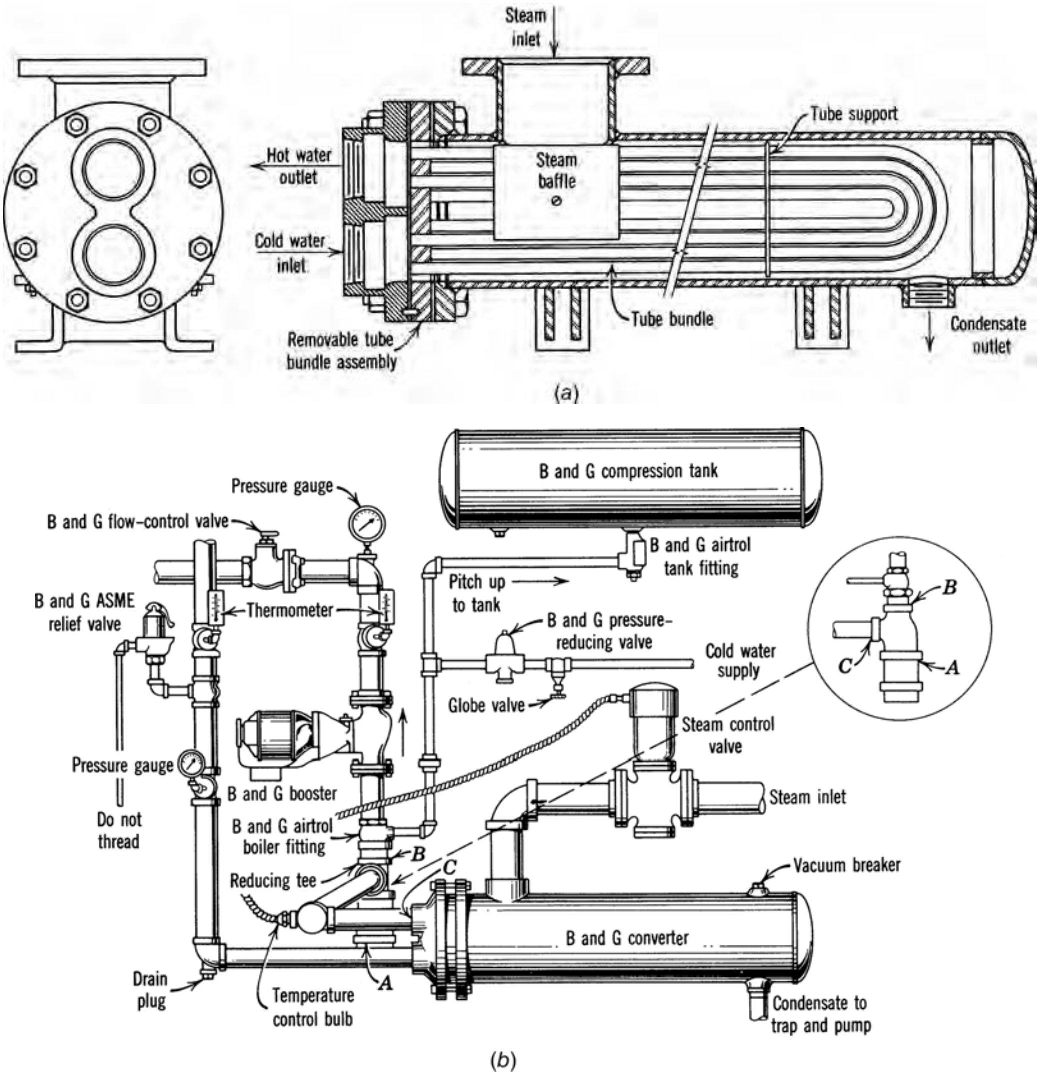


Fig. 12.14 *Conversion unit that transfers heat from steam to hot water. (a) Section illustrating the principle of heat transfer from steam to water. (b) A converter connected to the steam supply and equipped with all devices necessary for a complete hot water heating system. (Courtesy of ITT Bell and Gossett.)*

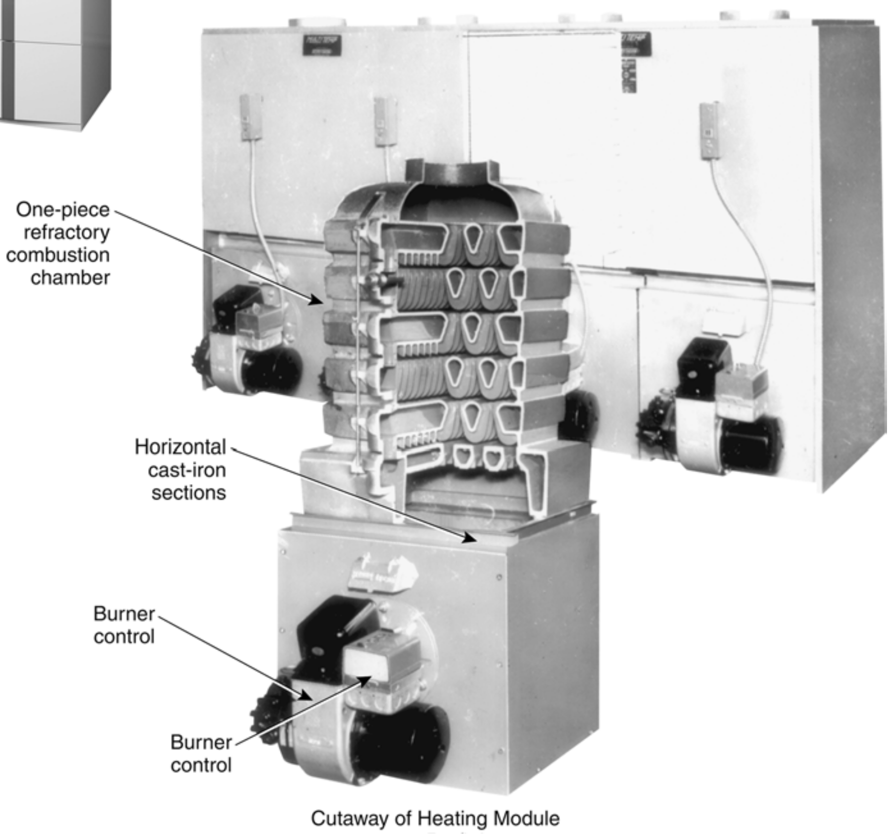
Pulse boilers operate with lower water temperatures so that water vapor in the flue gas can condense and drain. This change of state (or phase change) liberates additional heat, allowing these pulse boilers to achieve efficiencies up to 90%. They exhaust moist air, not hot fumes, so flues can be small-diameter plastic pipe rather than large-diameter, heat-resistant materials. The upcoming discussion regarding the appurtenances that come with on-site combustion may help place these comments in perspective.

The boilers in the preceding discussion tend to be used in larger building applications. Residential applications will tend to employ the following boiler types:

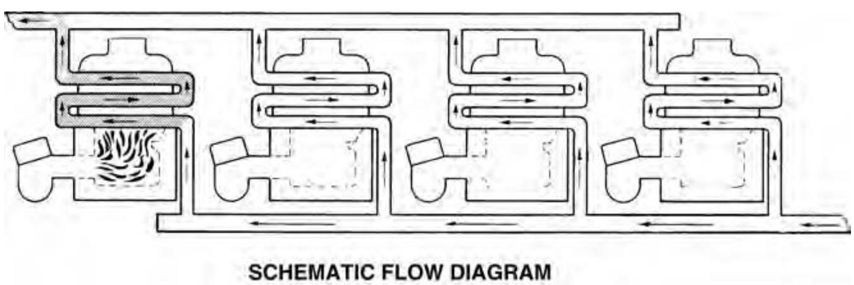
Oil-fired steel boiler: A refractory chamber receives the hot flame of the oil fire. Combustion continues within the chamber and the fire tubes. Smoke leaves through the breeching at the rear. Water, *outside* the chamber, receives the heat generated in the combustion chamber. If a domestic hot water coil is included, a larger-capacity boiler

Fig. 12.15 *Modular boilers. (a) A bank of two modules—with a total input of 1.5 million Btu/h (439 kW). (b) Details of a module (20 × 32 × 48 in. H [510 × 812 × 1220 mm]) with a 385,000 Btu/h (113 kW) input. (c) Schematic showing multiple boiler flow conditions in mild weather, with only one module in operation. (Courtesy of Slant/Fin.)*

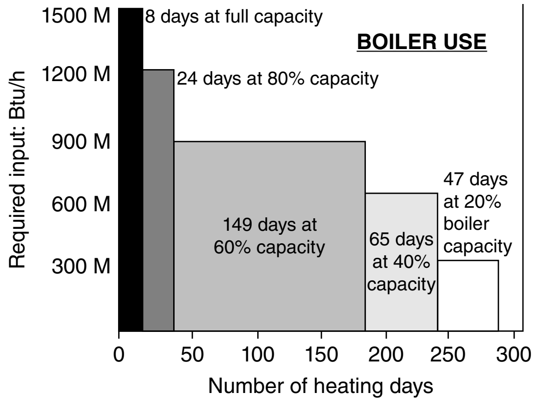
(*a*)



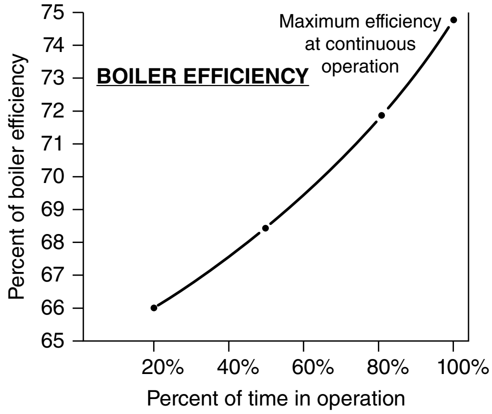
(*b*)



(*c*)



(*a*)



(*b*)

Fig. 12.16 *One large boiler versus many smaller ones. (a) Boilers rarely operate at full capacity; instead, they respond to part loads the majority of the time. (b) Under part load conditions, a boiler will often short-cycle, which on a single large boiler could drop the annual efficiency into the 66% to 75% range.*

is selected to handle this additional load. An aquastat (water thermostat) turns on the burner whenever the boiler water cools below a designated setpoint, thereby maintaining a reservoir of hot water ready for heating the building.

Gas-fired cast-iron hot water boiler: Cast-iron sections contain water that is heated by hot gases rising through these sections. Output is related to the number of sections. Improved efficiency is gained through use of a heat extractor in the flue. With induced draft combustion, a condensing unit in the flue, and electronic ignition instead of a pilot light, up to 90% AFUE is attainable (Fig. 12.17). The American Gas Association (AGA) sets standards for gas-fired equipment.

Oil-fired, cast-iron hot water boiler: Primary and secondary air for combustion may be regulated at the burner unit. Flame enters the refractory chamber and continues around the outside of the water-filled cast-iron sections.

As fuels burn to produce heat, they require oxygen to support the combustion process. Because oxygen constitutes only about one-fifth of the volume of air, reasonably large rates of airflow are required. The air should be drawn from outdoors at a position close to the fuel burner or (preferably) led to the burner location by a duct. Combustion air should *not* be drawn from the general building volume. Doing so is a waste of energy, and contemporary “tight” construction inhibits replacement airflow through the building envelope, creating a dangerous condition.

Prefabricated chimneys (Fig. 12.18*b*) have replaced bulkier and heavier field-built masonry chimneys. They offer a number of advantages and can be easily supported by a normal structure. Further, high-efficiency boilers and furnaces manage to remove so much heat from the exhaust gases that smaller flues operating at much lower temperatures result. These relatively small pipes can be vented through a wall to the exterior. Eliminating a chimney has lessened the impact on the building design of combustion-based boilers and furnaces.

For older or less-efficient fuel-burning equipment, it is important that chimneys carrying high-temperature flue gases be safely isolated from combustible construction to prevent the possibility of fire. The size of a flue will depend upon the capacity of the boiler or furnace. Flue height had traditionally been 35 to 40 ft (11 to 12 m). Providing a draft, for which chimney height was an important consideration, is now accomplished by fans. Draft hoods above gas burners prevent downdraft from blowing out the flames.

The storage space to be provided for fuel oil or propane depends upon the proximity of the supplier and the space available at the building site. For oil, when more than 275 gal (1040 L) was stored, it was previously common practice to use an outside tank buried in the ground. This practice eventually led to leaking tanks and contaminated soil and groundwater. Several factors have converged to discourage

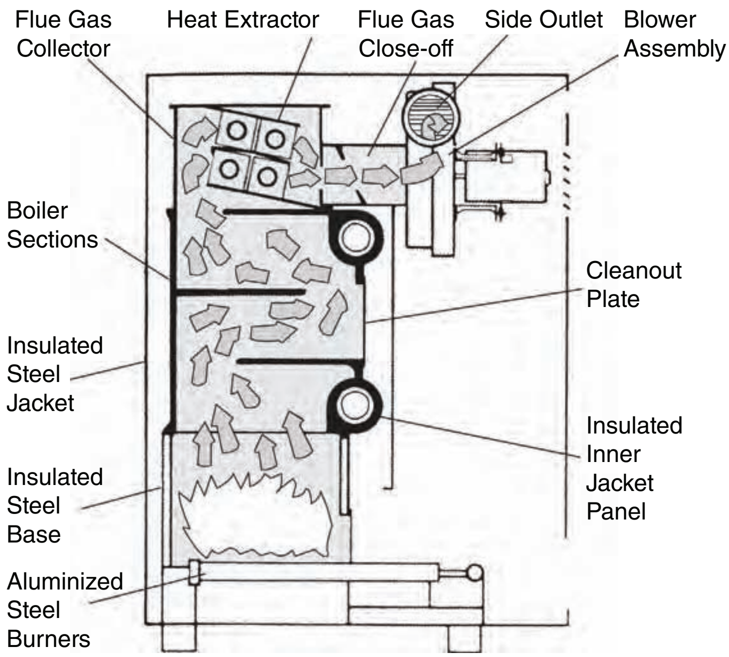


Fig. 12.17 *Gas-fired cast-iron sectional boiler for hot water heating. Very high operating efficiency is possible; no chimney is required, as low-temperature exhaust gases can be vented through a wall to the exterior.*

the use of oil in newer buildings: a cleaner and more efficient alternative (natural gas), few basements in new residential construction where oil tanks might be placed, and a dislike of unsightly aboveground oil tanks.

Hot water boilers are rated according to heating capacity using several metrics. Heating capacity is the rate of useful heat output when the boiler is operating under steady-state conditions, often expressed in MBh (1000 Btu/h). The term "useful heat" assumes that the boiler is within the heated envelope of the building; thus, any heat that escapes through the boiler walls is available to help heat the building. AFUE, the annual fuel utilization efficiency, as discussed in Section 12.4(e), is used to express boiler performance. In addition, net I = B = R ratings (a designation of the Institute of Boiler and Radiator Manufacturers) are published by the Hydronics Institute Division of the Gas Appliance Manufacturers Association (GAMA). (The term "hydronic" refers to the use of water as a heat-transfer medium.) The net I = B = R rating load is lower than the heating capacity rating, because it consists only of the heating to be delivered to the spaces and excludes the heat loss of the boiler itself.

Select a boiler whose rating matches the calculated design heat loss of the building; too small a boiler results in lower indoor temperatures at design conditions; too large a boiler costs more and is a waste of space. If using AFUE to select an efficient boiler, ensure that the assumptions about "inches of water draft" and percentage CO_2 are similar for the boilers being compared. Minimum acceptable AFUEs are specified in ANSI/ASHRAE/IESNA 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

(c) Furnaces

Furnaces provide the heating effect required to elevate air temperature to a point where it can be used for building heating. A furnace produces hot air that can be distributed to spaces via a central ductwork system; local furnace configurations without ductwork are also available. The heat source for a furnace is most commonly on-site combustion (using natural gas, propane, or fuel oil) or electric resistance. A combustion furnace will require outdoor air to support the combustion process, a flue to vent products of combustion to the outdoors, and

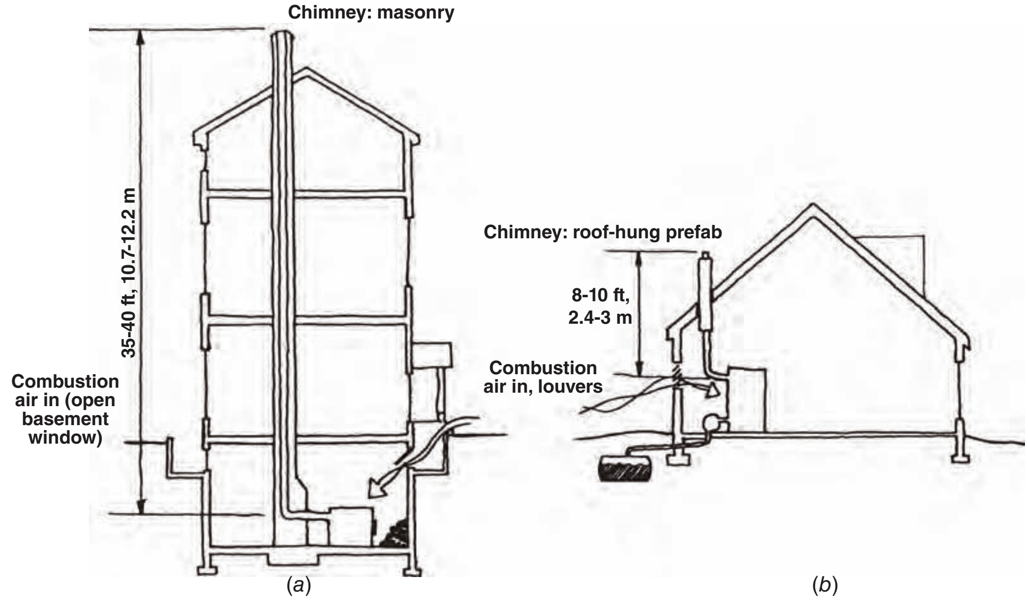


Fig. 12.18 *The historic need for 40-ft (12-m) chimneys (a) has been eliminated by controlled draft in burners (b) and by the use of high-efficiency heating equipment that can be directly vented to the exterior through prefabricated chimneys. Note the buried fuel oil tank, an architectural consideration and potential environmental concern.*

perhaps fuel storage capabilities (if the fuel used is not an on-demand utility)—see Fig. 12.18. Heat transfer can also be used as the heat source for a furnace via a coil connected to a heat pump system. Energy capture is also a possible heat source (perhaps from an air-based solar thermal collector).

The term "furnace" is generally used to describe residential-scale equipment. In larger building applications, an air-handling unit will perform the same basic functions as a furnace. In addition to coupling a heat source to circulating air, a furnace will contain a fan to provide the motive force to circulate that air, and a filter to clean the air passing through the unit. Controls will also be provided to ensure safe and effective operation. These components are all included in a packaged sheet-metal enclosure. Vertical and horizontal configurations (Fig. 12.19) are available to provide flexibility in installation.

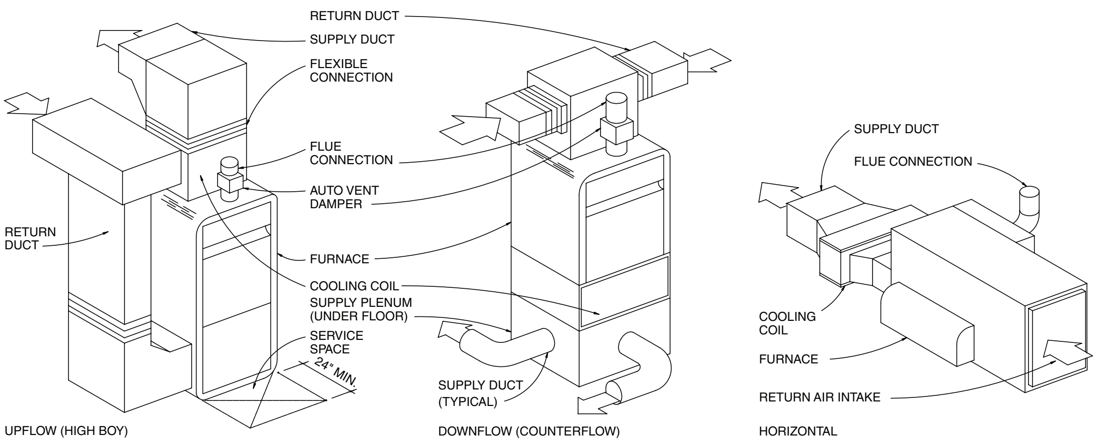


Fig. 12.19 *Typical furnace types. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *10th ed.; © 2000 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

(a)

(b)

Fig. 12.20 *Furnaces with greatly increased operating efficiencies are now available. (a) An Amana gas furnace. (b) The small, high-efficiency heat exchanger utilized by this furnace, which recovers heat from exhaust gases. (Courtesy of Amana Refrigeration, Inc.)*

Furnaces have become much more efficient over the past decades, thanks to forced-draft chimneys and improved heat exchangers, as shown in Fig. 12.20. Seasonal efficiencies of up to 95% are possible, in contrast to 65% or so for older furnaces. AFUE ratings for high-efficiency furnaces are based on an isolated combustion system that requires that all combustion air be drawn from outside (instead of from the occupied volume of a building).

(d) Wood-Burning Appliances

After passive solar heating, the most ancient method of heating is the radiant effect of fire. With each improvement from campfire to fireplace to wood stove, more of the heat from the fuel was captured for use rather than wasted to the outdoors (Fig. 12.21). Although many people enjoy the sight, sound, and smell of an open fireplace, a tightly enclosed wood stove with a catalytic combustor is a substantially more efficient and less polluting approach to heating. Indoor as well as outdoor air pollution is a serious issue with fireplaces and stoves. Combustion generates carbon monoxide, breathable particulates, and, at times, nitrogen dioxide. Wood smoke can cause nose and throat irritation, it can remain in the lungs, and it can trigger asthmatic attacks. Keeping a clean chimney, burning small, hot fires rather than large, smoky ones, using seasoned wood, and ensuring adequate ventilation to the wood-burning device are strategies to minimize pollution and health and fire risk.

Open fireplaces may be lovely to look at, but the amount of air exhausted up the chimney can

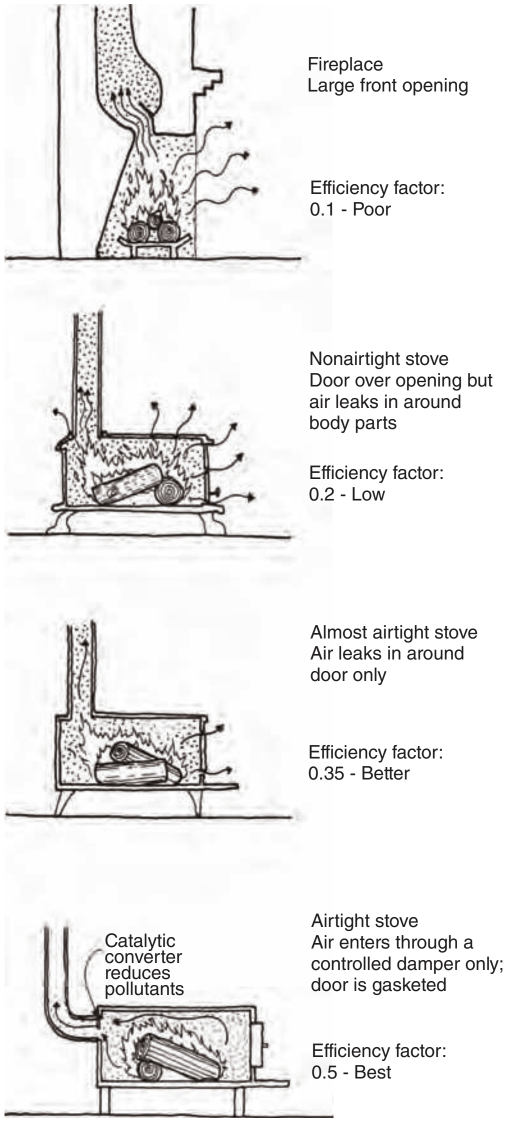


Fig. 12.21 *Wood-burning devices have substantially increased in efficiency since the time of the open fireplace. (Copyright © 1978 by* Alternative Sources of Energy, *Issue 35.)*

quickly cause more heat loss than heat gain from the fire. The colder the outdoor air, the greater the net heat loss. Masonry mass around fireplaces can store and release some heat; for energy conservation, the mass should be surrounded by the building rather than located on an exterior wall. Building codes typically require a fireplace to have a tight-fitting damper, firebox doors, and a source of outside combustion air feeding the firebox.

Wood stoves are available in a wide variety of styles and are made of several materials. The heating capacities of such stoves are often difficult to determine. Manufacturers rarely specify the Btu/h output, which depends upon the density, moisture content, and burn time of the wood fuel. Wood that has been split, loosely stacked, and protected from rain for at least six months should achieve a moisture content of about 20% by weight. The following sizing procedure assumes no more than this 20% moisture content. For more details, see Issue 35 of *Alternative Sources of Energy* magazine (1978).

The formula for the hourly heat output to a room from a wood stove is

$$\text{Btu/h} = \frac{(V)(E)(D)(7000)}{T}$$

where

V = useful (loadable) volume of the stove (ft^3)

E = percent efficiency, expressed as a decimal (<1.0); see Fig. 12.21

D = density of the wood fuel (Table 12.2)

T = burn time (hours) for a complete load of firewood; usually assumed as 8 hours at a minimum

7000 = Btu/lb of firewood, 20% moisture content

TABLE 12.2 Approximate Average Wood Density

Type	Density lb/ft^3 (kg/m^3)[a]
Shagbark hickory	40.5 (648)
White oak	37.4 (598)
Red oak	36.2 (579)
Beech	36.2 (579)
Sugar maple	34.9 (558)
Yellow birch	34.3 (548)
White ash	33.7 (539)
Black walnut	31.2 (499)
American elm	28.7 (459)
Spruce	25.6 (410)
Hemlock	23.7 (379)
Aspen	23.1 (370)
Red cedar	18.7 (299)
White pine	17.5 (280)

Source: Alternative Sources of Energy, Issue 35, © 1978. Reprinted by permission.

[a]These values are approximate; they vary a great deal. SI units added by the authors of this book.

"Bone-dry" wood can be assumed to have 8600 Btu/lb (20,000 kJ/kg). Note that a reduction in burn time increases the heat output; when the air supply to the stove is increased, the fire burns hotter, consuming the wood more quickly. To meet the design heat loss (worst reasonable condition) for a room, burn times of 8 to 10 hours should be assumed. Stoves rarely need relighting with a 10-hour burn time.

Pellet stoves were first introduced in 1984 and have several desirable characteristics. The pellets are made from densified quality sawdust, a manufacturing by-product. The form and content of this fuel produce a highly efficient burn with less pollution emitted. The fuel is cleaner and takes less storage space than cordwood; an electric auger automatically feeds fuel into the burnplace to maintain a fire. From 10,000 to 50,000 Btu/h (2930 to 14,650 W) can be produced, depending on the model and operating settings.

Wood stoves are frequently used as the sole active heat source for an entire building, such as a residence or a small commercial building that is passively solar heated. Because radiation is the dominant form of heat output, the areas that "see" the stove get most of the benefit. *Circulating stoves*, however, convert a larger portion of their heat to convection, which produces a layer of hot air at ceiling level. By providing a path between rooms at ceiling height, this hot air can slowly spread throughout a building; it can also easily find its way upstairs, because warm air rises. The more thermally massive the ceiling construction, the longer it can store and reradiate the heat from the stove.

The flue leading from a wood stove carries very hot gases that are a potential source of heat (and pollution). The flue can be exposed to a space, making radiant heat available, or simple heat exchangers can be constructed (such as for the preheating of domestic hot water). More elaborate heat recovery devices—for boiler flue heat recovery—are commercially available.

Catalytic combustors reduce the air pollution that results from burning wood. These devices are honeycomb-shaped, chemically treated disks as much as 6 in. in diameter and 3 in. thick (150 mm in diameter, 75 mm thick). They are either inserted into the flue or built into the stove itself. When wood smoke passes through the combustor, it reacts with the chemical treatment and ignites at a much lower temperature; this causes combustion products to burn that otherwise would have gone up the flue. The result is more heat produced, less creosote buildup in the flue, and fewer pollutants in the atmosphere. Like the catalytic converters in autos, these devices impose limits on the fuel: plastic, colored newsprint, metallic substances, and sulfur are ruinous to combustors; this simply means that the stove must be used as a wood burner, not a trash incinerator.

Wood stoves have a larger impact on building design than do most other heating devices. Noncombustible materials must be placed below and around a stove or a minimum clearance to ordinary combustible building materials must be provided. Furniture arrangements and circulation paths must be designed with the very hot stove surfaces in mind. Hot spots occur near the stove; cold spots occur whenever visual access to the stove is blocked. Thermally massive materials near the stove are advantageous in leveling the large temperature swings that can accompany the on–off cycle of the stove; this affinity for thermal mass has made the wood stove a popular choice for backup heat in passively solar-heated buildings. Finally, the amount of space required for wood storage should not be overlooked; recall the impact of the wood storage space on the house shown in Fig. 2.2. A covered, well-ventilated, easily accessible, and quite large space is desirable.

Masonry heaters overcome many of the disadvantages of a metal wood stove. Their footprint is rather small compared to their height; typically, they are used to heat an entire building (such as a residence). An inner vertical firebox supports a hot, clean burn, resulting in efficient combustion; combustion gases then flow downward in outer chambers, transferring heat to exterior masonry surfaces. In Finnish masonry heaters, this is termed *contraflow* (Fig. 12.22). Cool air at the floor of the room flows upward as it is heated by contact with this masonry; the temperature difference between masonry and air remains fairly constant, with the highest temperatures at the top. Heat is gentle and even; dangerously hot surfaces are avoided. Fires may be built at 6:00 P.M., and combustion is completed by bedtime; the heat continues to radiate all night, but no fire is burning while people sleep. Research at Finland's Tampere University of

Fig. 12.22 *The Finnish contraflow masonry heater.*

Technology has resulted in very effective masonry heater designs, described in Barden and Hyytiäinen (1993).

(e) Infrared Heaters

Infrared heaters are often seen in semi-outdoor locations such as loading docks, repair shops, and higher-end bus shelters. They are fired with either natural gas or propane, or powered by electricity. When vented, they can be used in more traditional environments such as the retail store in a remodeled warehouse shown in Fig. 12.23. Their advantage is that they heat surfaces first rather than air, so that comfort is obtained without the need for high air temperatures. When high rates of air exchange are expected, high-intensity radiant heaters are often used.

Radiant heaters should be sized by the surface temperature change they produce. Many manufacturers specify this surface Δt for specified mounting heights and angles relative to the surface of interest.

(*a*)

(*b*)

Fig. 12.23 *A high-intensity infrared heater adds to the historic atmosphere of this retail store in an old warehouse (a). Exposed mechanical equipment includes the chains that operate the clerestory windows. The vented gas heater has an adjustable reflector that enables its radiant heat to be directed. (b) Vented gas high-intensity infrared heaters are available in both straight-line and U-shaped units. ([a] Clark-Ditton Architects, Eugene, OR.) ([b] Courtesy of Solaronics, Inc., Rochester, MI.)*

12.7 SOURCE COMPONENTS: COOLTH

An HVAC system that will be asked to provide cooling to offset building heat gains needs a coolth source. There are three conceptually (and physically) different means of introducing coolth into a building. These three basic approaches mushroom into dozens of specific equipment options—and these options expand into more dozens of specific equipment offerings.

Vapor compression refrigeration: The vapor compression cycle is a mechanical-electrical circuit in which a refrigerant is circulated under temperature conditions that allow it to pick up heat from within a building and dump heat to the outside environment (under weather conditions that won't permit passive heat flow from in-to-out). Vapor compression is by far the most commonly used and encountered means of producing a cooling effect for an HVAC system. All vapor compression systems require an externally placed heat rejection unit (a condenser). The capacity of vapor compression equipment covers a wide range (from small to huge); the specifics of equipment types is also diverse. The vapor compression cycle can be used directly to cool air or to produce chilled water. Capacity is expressed in tons of cooling and "efficiency" via COP (which will be above 2.0).

Absorption refrigeration: The absorption refrigeration cycle is diagrammatically similar to the vapor compression cycle—but employs a chemical refrigerant flow process driven by heat (versus mechanical compression). Absorption refrigeration equipment is less efficient (has a lower COP) than comparable vapor compression equipment, but may be driven by waste heat, solar hot water, or natural gas. Absorption equipment today is typically used to produce chilled water in moderately large capacity applications. The equipment can be quieter than comparable vapor compression equipment.

Evaporative cooling: In an HVAC system, an evaporative cooling effect will be produced by equipment called an evaporative cooler. This approach to coolth production can be very energy efficient (operating as it does along a line of approximately constant enthalpy); COP values can reach 15–20. With variations in equipment type, evaporative cooling can be used to directly cool air or to cool water. The performance of an evaporative cooler is more dependent upon climate than that of either vapor compression or absorption refrigeration (low relative humidity is generally desirable, although indirect evaporative cooling can extend the climate range of applications). Where feasible, evaporative cooling has interesting potential as a low-GWP (global warming potential) high-efficiency coolth source.

Several examples of coolth source equipment and applications are provided in Section 12.8 by way of introduction to this part of an HVAC system.

12.8 COOLING EQUIPMENT

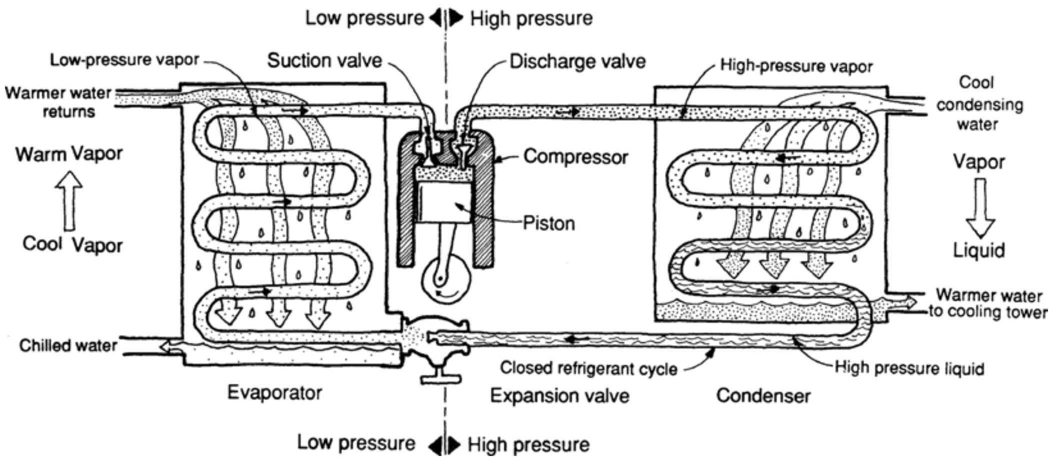
The fundamental question that faces the designer of an active cooling system is how to get heat to flow from a cooler indoor environment to a hotter outdoor environment—which is the situation faced during the overheated portions of the year. Rather than violate the laws of thermodynamics, a refrigeration cycle sets up a manufactured intermediary thermal system that exhibits desirable temperature regimes that will support this "uphill" heat flow. This intermediating system comes with a cost—in terms of equipment, energy, and environmental pollution—but it allows us to be comfortable under conditions that 100 years ago would have been most uncomfortable. The two refrigerant-based cooling processes commonly used in buildings are the *vapor compression* and the *absorption* refrigeration cycles. The vapor compression cycle can be adapted to a huge range of capacities and a variety of configurations (such as direct expansion [DX] or chiller arrangements). Heat rejection to the outdoors may be accomplished through an air-cooled condenser or via a cooling tower. Vapor compression cooling is used in at least 95% of HVAC systems.

(a) Vapor Compression Refrigeration

Figure 12.24 illustrates a water-cooled vapor compression cycle. The system acts as a thermal bridge between one water system (chilled water) and another water system (condenser water). Heat is removed from a building via the chilled water and rejected from the building via the condenser water—thus cooling the building. The cycle operates by cyclical liquefaction and evaporation of a refrigerant, during which processes the refrigerant releases and absorbs heat, respectively.

Refrigerants are the heart of a refrigeration cycle. To liquefy a gaseous refrigerant (Fig. 12.24), it is first compressed to a high-pressure vapor; then, by means of a heat sink, latent heat is extracted from the refrigerant, which condenses it to a liquid. The resulting high-pressure liquid has a potential for heat absorption only after it is passed through an expansion valve where it is depressurized and allowed to expand back to its gaseous form. During this change of state, the refrigerant must take on latent heat by reducing its own temperature and subsequently drawing heat out of the building.

A refrigeration cycle is a heat-circulating system. Heat is pumped out of a building through the refrigeration cycle. This pumping action was



Interactive Animation

Fig. 12.24 *Schematic arrangement of a compressive refrigeration cycle, providing chilled water for a building cooling system.*

originally conceived as a unidirectional process. By reverse cycle arrangements of the vapor compression components, however, heat flow in the other direction (from the outdoors to the indoors) can be accomplished. A cooling-only cycle is called a refrigeration system. A bi-directional (heating and cooling) cycle is called a heat pump. The compressive refrigeration cycle can be used to transfer heat between almost any media; Fig. 12.24 illustrates a water–water cycle, Fig. 12.40 shows a heat pump in both air–air and water–air applications.

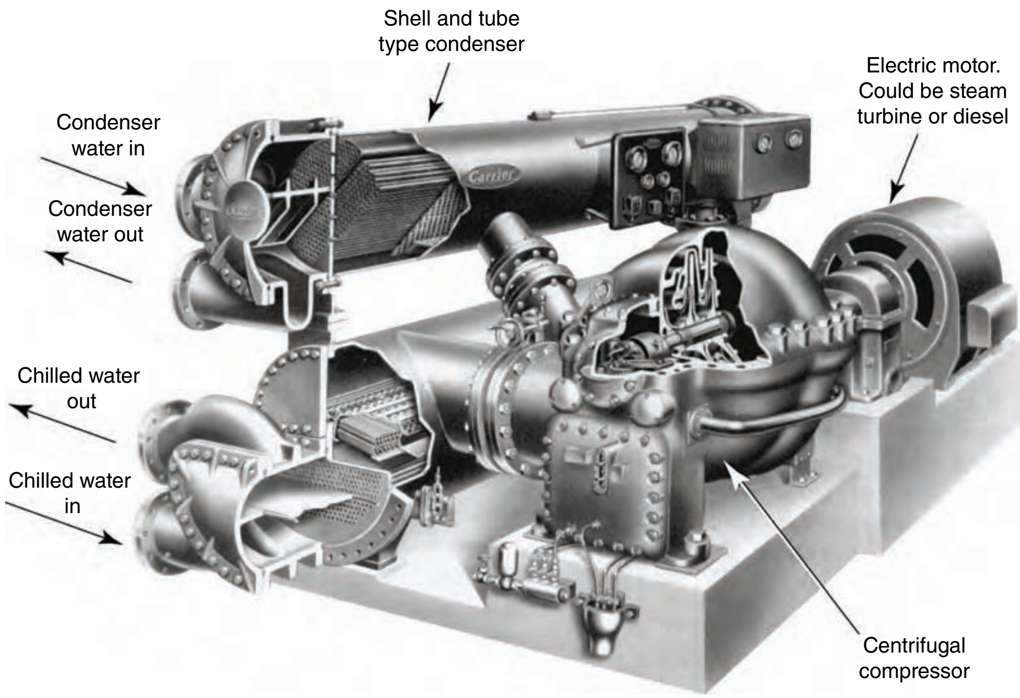
The piston-type compressor shown in Fig. 12.24 is one option. The compressor can instead be one of several other types: *rotary*, *scroll*, or *screw*, each with characteristics suitable to particular applications. Large refrigeration units are usually *centrifugal chillers* (Fig. 12.25), with compressors that can be driven either by an electric motor or a turbine driven by steam or gas. When a steam-driven turbine is used, the exhaust steam is often used to drive an auxiliary absorption cycle machine. The coupling of these two devices makes an efficient combination (and the steam plant that supplies them in summer can supply heating in winter). Centrifugal chillers usually require about 1 hp/ton (0.57 kW, or 10 ft^3 gas, or about 15 lb of steam per ton). These chillers usually use a cooling tower as the heat rejection device. *Dual-condenser chillers* (Fig. 12.26) can reject heat to a cooling tower (via a heat rejection condenser) or to building heating uses (via a heat recovery condenser).

Medium-capacity chillers may use either twin screws or a scroll compressor. The screw compressor (Fig. 12.27) has a pair of helical screws; as they rotate, they mesh and thus compress the volume of the refrigerant gas. They are small and quiet, with little vibration. The scroll compressor (Fig. 12.28) uses two inter-fitting spiral-shaped scrolls. The refrigerant gas is compressed as one scroll rotates against the other fixed scroll. Quiet and low-maintenance, they are more efficient than reciprocating compressors.

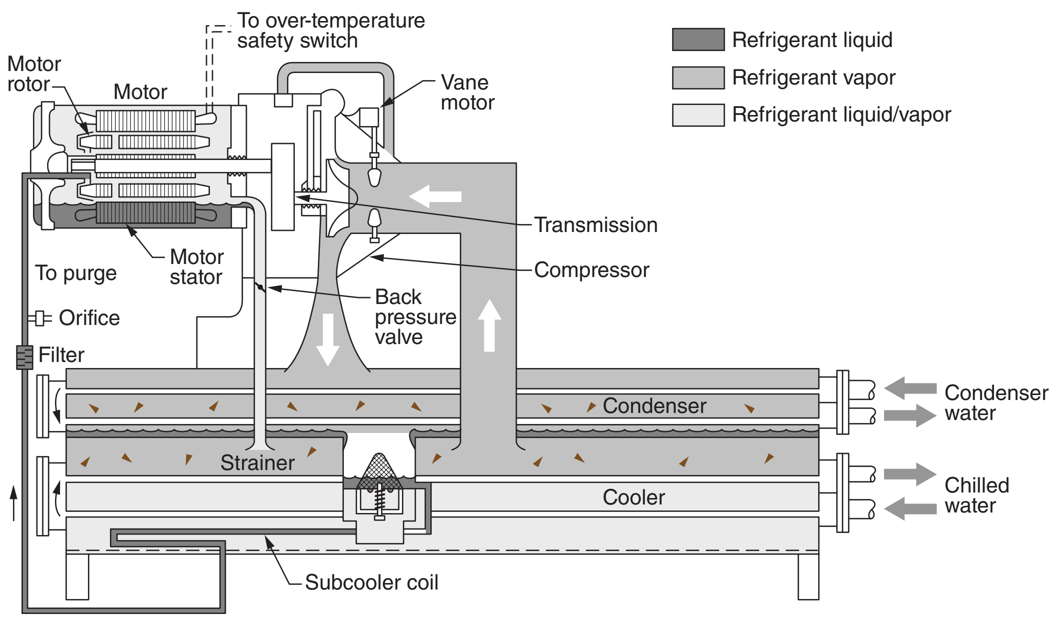
Reciprocating chillers (Fig. 12.29) are small-capacity vapor compression machines. Usually electrically driven, they are often combined with an air-cooled heat rejection loop rather than a cooling tower.

Chilled water is usually supplied at between 40° and 48°F (4° and 9°C). When the chilled water is supplied cold and returns much warmer, the large rise in temperature reduces the initial size (cost) of equipment and increases its efficiency (thereby reducing the operating cost as well). Water treatment may be needed for chilled water, to control corrosion or scaling.

Typical cooling capacities and space requirements for chillers are shown in Fig. 12.30—with dimensions as indicated. Each refrigeration machine in this illustration requires two pumps—one for the



(*a*)



(*b*)

Fig. 12.25 *(a) A large capacity centrifugal chiller—using the vapor compression refrigeration cycle. (Courtesy of the Carrier Corporation.) (b) Centrifugal chiller with a flooded cooler and condenser within a single outer shell. This low-pressure unit typically produces 100 to 400 tons (350–1400 kW) of cooling. Typical dimensions are: 14 ft L × 5 ft W × 8 ft H (4.3 × 1.5 × 2.4 m); weight 16,000 lb (7260 kg). (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *7th ed.; © 1981 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

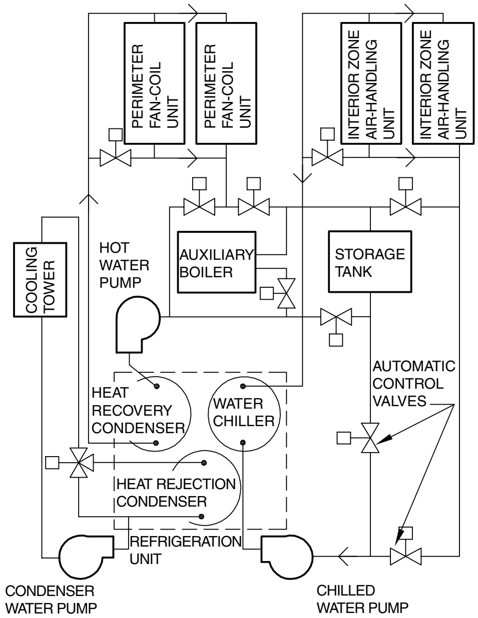


Fig. 12.26 *Dual-condenser chiller. The heat removed from the chilled water loop is either rejected to the cooling tower or recovered for building heating. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

chilled water (supplied to the building loads) and one for condenser water (that circulates to a cooling tower). Typically, space is provided for future chiller additions, which may be required by building expansion and/or by higher internal gains from as-yet-uninstalled plug loads. Improved-efficiency chillers may replace older ones when energy costs and environmental regulations become compelling. Adequate clearance and access to the equipment room is a major design issue.

Refrigerants: A refrigerant should have desirable temperature-pressure relationships such that

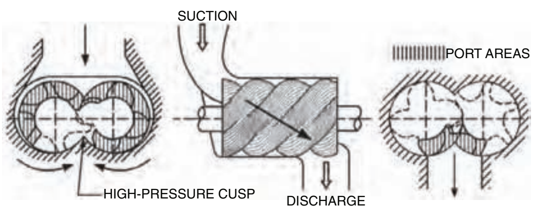


Fig. 12.27 *A screw, or helical, compressor is a quieter, smaller machine with little vibration. (Reprinted with permission; ©ASHRAE 2012 ASHRAE Handbook—HVAC Systems and Equipment.)*

it can operate at a condensing temperature above the outdoor air temperature when used in an air-cooled configuration, and at an evaporator temperature below room air temperature when in DX configuration—with a reasonable expenditure of energy for pressurization. A rather large number of compounds fit this description and have been used as refrigerants for various applications. In addition to desirable temperature-pressure characteristics, it would be nice if a refrigerant were nontoxic, low-cost, long-lived, not too viscous, and environmentally benign. This last characteristic is taking on increasing importance to the HVAC industry.

The refrigerants most commonly used during the 1990s (chlorofluorocarbons; CFCs) were a serious threat to the atmosphere. Production of CFC refrigerants was banned in the United States in the mid-1990s. Fears that replacement refrigerants would be less efficient have largely disappeared; combinations of better chillers and new refrigerants produce energy savings. The energy aspect of refrigeration is intriguing. CO_2 is released during the production of the electricity that will power chillers and other refrigeration machines. There is a quandary if lower-GWP refrigerants are also less efficient and therefore require higher energy consumption. This discussion assumes continued power generation from fossil fuels; if renewable power sources (wind, PV) are used to power cooling equipment, then this aspect of climate change can be mitigated.

Refrigerants have been improved, but still pose an environmental threat because they can escape from equipment during operation or repair as gases that mix into the atmosphere. The two key threats are stratospheric ozone depletion and climate change. The potential of a refrigerant to harm the ozone layer is expressed by its ODP (ozone depletion potential) value. GWP (global warming potential) is a measure of the ability of a refrigerant to effect climate change. Considerable efforts are under way both to reduce the likelihood of escaping refrigerant and to develop more efficient non-CFC refrigerants.

Hydrochlorofluorocarbon (HCFC) refrigerants are an interim replacement for CFCs—they are still a threat to the atmosphere, but not as great as CFCs. An HCFC contains chlorine, a major influence on ozone depletion. Thus, HCFCs are due to be phased out in the decades following the year 2000. A longer-term replacement option involves hydrofluorocarbons (HFCs); even this alternative

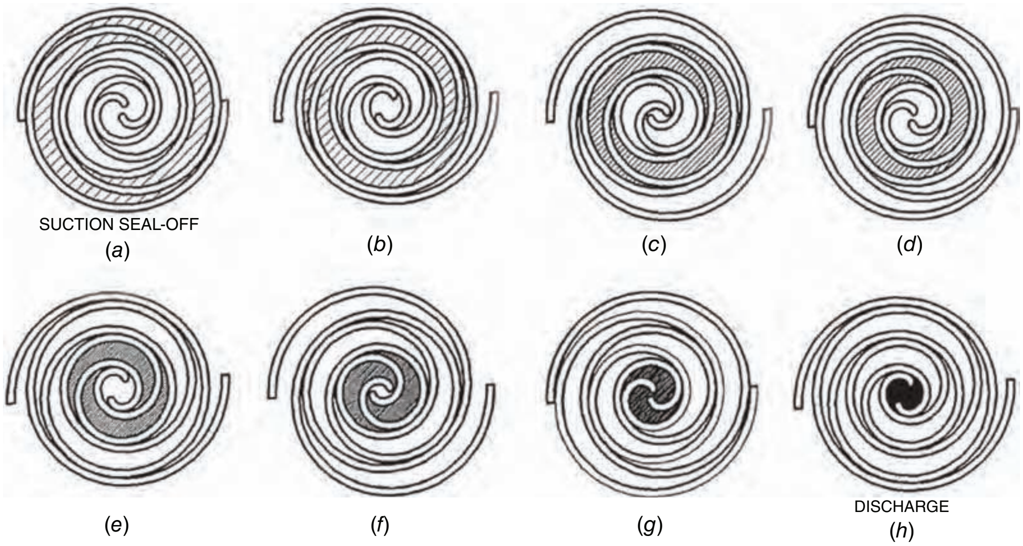


Fig. 12.28 *The scroll compressor rotates one scroll element against another, with a quiet and efficient compression of the refrigerant. (Reprinted with permission; ©ASHRAE 2012 ASHRAE Handbook—HVAC Systems and Equipment.)*

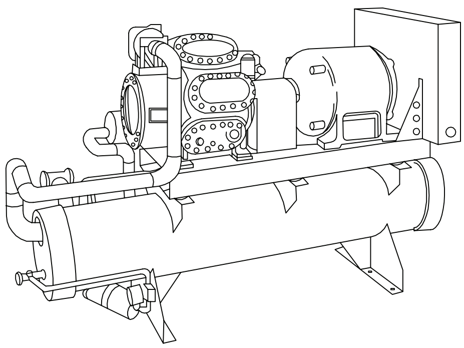
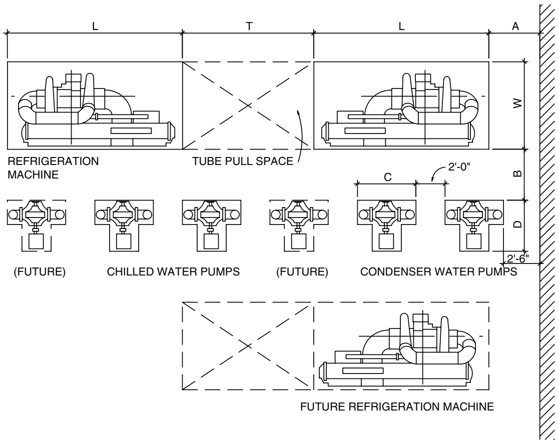


Fig. 12.29 *A reciprocating chiller—a small-capacity machine that uses the compressive refrigeration cycle. This type of chiller typically produces less than 200 tons (700 kW) of cooling. Such a machine might be around 8 ft L × 3 ft W × 5 ft H (2.4 × 0.9 × 1.5 m) and weigh 3500 lb (1590 kg). (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

threatens the atmosphere. Yet another possibility is natural hydrocarbons (HC). In general, comparing these two alternatives, HFCs have higher global warming potential and long atmospheric lifetimes, but they have low toxicity and are nonflammable. HCs have negligible global warming potential and short atmospheric lifetimes, but are flammable and explosive. Another alternative is ammonia, used in the early years of vapor compression refrigeration but discontinued because of its acute toxicity and flammability. It is now returning in some refrigeration cycles. Carbon dioxide as a refrigerant is also seeing a resurgence in interest. Research will ideally sort this situation out. For a comprehensive review of refrigerants, see Calm (1994).

Direct expansion refrigeration: The preceding discussion of vapor compression refrigeration cycles tended to focus on chillers—which provide cooling effect through the medium of chilled water circulated to loads located within a building. A direct expansion (DX) refrigeration cycle provides cooling effect through the action of room air passing across a coil that contains circulating refrigerant. A DX system is simpler than a chiller system, but has application limitations. In general, the evaporator coil (cooling coil with refrigerant) can be located only 100 ft (30 m) or so from the compressor of the system. DX systems tend to be close-coupled, which may be a limitation in larger buildings. DX refrigeration systems are very commonly used in smaller-scale buildings. Figure 12.31 illustrates a basic DX system—this diagram will form the basis for ensuing discussion of heat pump systems.

Variable refrigerant flow (VRF): The typical DX refrigeration cycle has one evaporator (cooling) coil paired with one compressor/condenser. In a



General

The capacity of each refrigeration machine is equal to 50% of the peak cooling load. Each water pump provides the flow requirement of one refrigeration machine. Therefore, one pair of condenser and chilled water pumps is needed for each machine.

The cooling lower may be located on the roof of the refrigeration equipment room or on the ground adjacent to the equipment room. When located on ground, the condenser water outlet(s) on the cooling tower must be not less than 5 ft above the equipment room floor elevation for proper functioning of condenser water pumps.

See ASHRAE Standard 15-2013 “Safety Standard for Refrigeration Systems” for required ventilation of chiller plant and monitoring of toxic refrigerants.

Expansion of Equipment

For operational flexibility of a refrigeration plant, the size of the future refrigeration machine is generally planned to be the same as of the present machines. It may be economically advantegeous to oversize some portions of the chilled and condenser water pipes to handle the future flow rates.

Provision must also be made for expansion of the cooling tower capacity when the future refrigeration machine is installed.

REFRIGERATION ROOM LAYOUT

REFRIGERATION EQUIPMENT ROOM SPACE REQUIREMENTS

	DIMENSIONS FT (M)								MINIMUM ROOM HEIGHT
EQUIPMENT: TONS (KW)	L	W	HEIGHT	T	A	B	C	D	
RECIPROCATING MACHINES									
Up to 50 (176)	10′-0″ (3.1)	3′-0″ (0.9)	6′-0″ (1.8)	8′-6″ (2.6)	3′-6″ (1.1)	3′-6″ (1.1)	4′-0″ (1.2)	3′-0″ (0.9)	11′-0″ (3.4)
50–100 (176–352)	12′-0″ (3.7)	3′-0″ (0.9)	6′-0″ (1.8)	9′-0″ (2.7)	3′-6″ (1.1)	3′-6″ (1.1)	4′-0″ (1.2)	3′-6″ (1.1)	11′-0″ (3.4)
CENTRIFUGAL MACHINES									
120–225 (422–791)	17′-0″ (5.2)	6′-0″ (1.8)	7′-0″ (2.1)	16′-6″ (5.0)	3′-6″ (1.1)	3′-6″ (1.1)	4′-6″ (1.4)	4′-0″ (1.2)	11′-6″ (3.5)
225–350 (791–1250)	17′-0″ (5.2)	6′-6″ (2.0)	7′-6″ (5.3)	17′-6″ (5.3)	3′-6″ (1.1)	3′-6″ (1.1)	5′-0″ (1.5)	5′-0″ (1.5)	11′-6″ (3.5)
350–550 (1250–1934)	17′-0″ (5.2)	8′-0″ (2.4)	8′-0″ (2.4)	16′-6″ (5.0)	3′-6″ (1.1)	3′-6″ (1.1)	6′-0″ (1.8)	5′-6″ (1.7)	12′-0″ (3.7)
550–750 (1934–2638)	17′-6″ (5.3)	9′-0″ (2.7)	10′-6″ (3.2)	17′-0″ (5.2)	3′-6″ (1.1)	3′-6″ (1.1)	6′-0″ (1.8)	5′-6″ (1.7)	14′-0″ (4.3)
750–1500 (2638–5276)	21′-0″ (6.4)	15′-0″ (4.6)	11′-0″ (3.4)	20′-0″ (6.1)	3′-6″ (1.1)	3′-6″ (1.1)	7′-6″ (2.3)	6′-0″ (1.8)	15′-0″ (4.6)
STEAM ABSORPTION MACHINES									
Up to 200 (703)	18′-6″ (5.6)	9′-6″ (2.9)	12′-0″ (3.7)	18′-0″ (5.5)	3′-6″ (1.1)	3′-6″ (1.1)	4′-6″ (1.4)	4′-0″ (1.2)	15′-0″ (4.6)
200–450 (703–1583)	21′-6″ (6.6)	9′-6″ (2.9)	12′-0″ (3.7)	21′-0″ (6.4)	3′-6″ (1.1)	3′-6″ (1.1)	5′-0″ (1.5)	5′-0″ (1.5)	15′-0″ (4.6)
450–550 (1583–1934)	23′-6″ (7.2)	9′-6″ (2.9)	12′-0″ (3.7)	23′-0″ (7.0)	3′-6″ (1.1)	3′-6″ (1.1)	6′-0″ (1.8)	5′-6″ (1.7)	15′-0″ (4.6)
550–750 (1934–2638)	26′-0″ (7.9)	10′-6″ (3.2)	13′-0″ (4.0)	25′-6″ (7.8)	3′-6″ (1.1)	3′-6″ (1.1)	6′-0″ (1.8)	5′-6″ (1.7)	16′-0″ (4.9)
750–1000 (2638–3517)	30′-0″ (9.1)	11′-0″ (3.4)	14′-0″ (4.3)	29′-6″ (9.0)	3′-6″ (1.1)	3′-6″ (1.1)	7′-0″ (2.1)	6′-0″ (1.8)	17′-6″ (5.3)

Note: Direct-fired absorption machines are roughly the same size as steam absorption machines.

Fig. 12.30 *Chiller room space requirements. Each refrigeration machine is served by two pumps (chilled water and condenser water). (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *10th ed.; © 2000 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

VRF system, one compressor/condenser unit can be connected to multiple evaporators. Each evaporator unit can be individually controlled (each is a thermal zone). This arrangement is similar to that found in ductless mini-split systems (Fig. 12.32), where one outdoor unit can be used with several evaporator units. Multi-split systems, however, turn on and off (like single-evaporator DX systems) to maintain room set-point temperature. VRF systems, on the other hand, continuously modulate the amount of refrigerant being sent to each evaporator in response to zone loads. By operating at varying speeds, VRF units work only at the needed rate, which is how they consume less energy than on/off systems, even if they run more frequently.

VRF systems are commonly available in heat pump or heat recovery configurations. A heat pump arrangement can provide either heating or cooling. A heat recovery arrangement permits coincident heating and cooling from one compressor/condenser unit, greatly increasing zoning flexibility. For detailed information on VRF systems see Chapter 18 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*.

(b) Absorption Refrigeration

This process (illustrated in Fig. 12.33) uses water as the primary refrigerant and lithium bromide (a salt solution) as the absorber. Heat drives this chemical process. Absorption refrigeration is less efficient (has

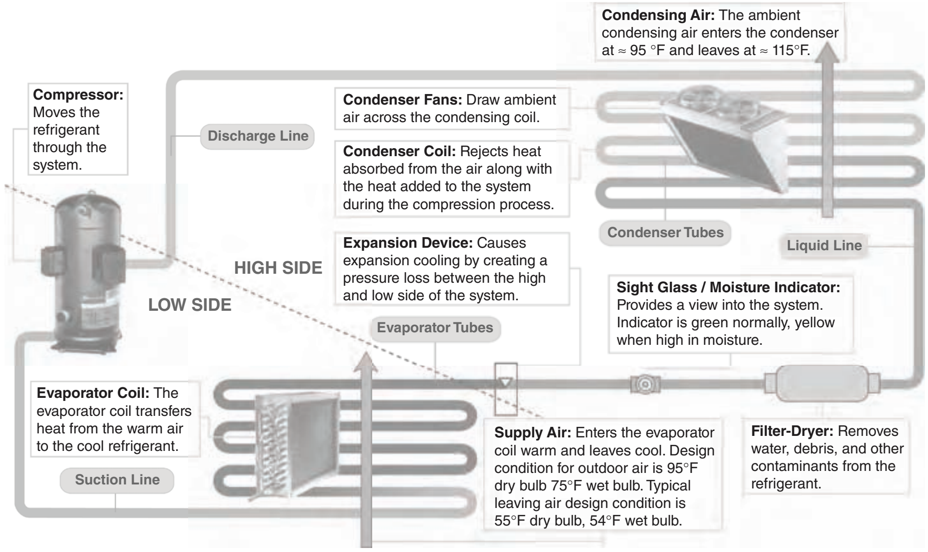


Fig. 12.31 *Schematic diagram showing a basic DX refrigeration system. (Courtesy of Greenheck Fan Corp.)*

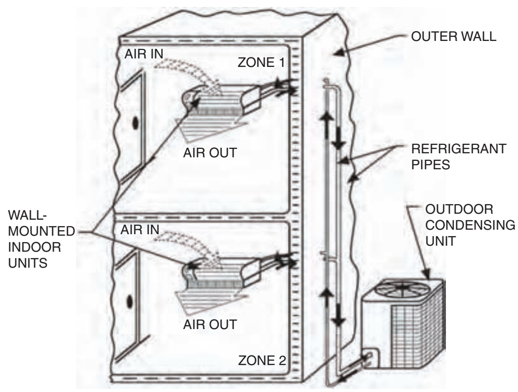
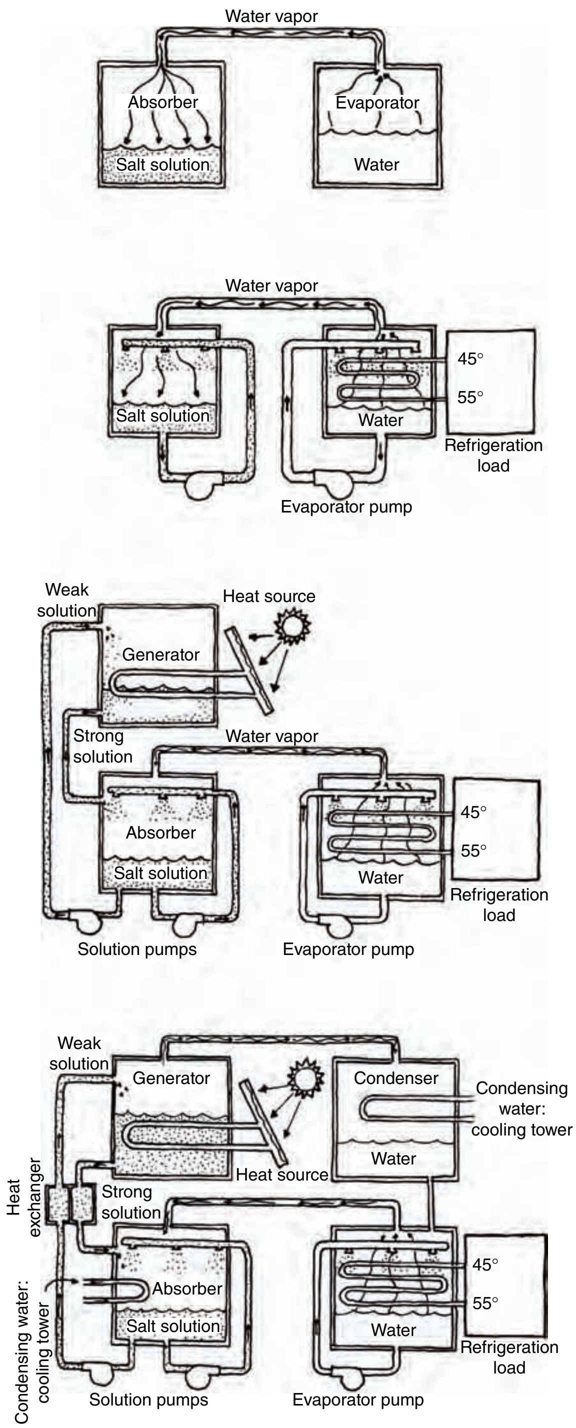


Fig. 12.32 *Ductless mini-split HVAC system. (Reprinted with permission; ©ASHRAE 2012 ASHRAE Handbook—HVAC Systems and Equipment.)*

a lower COP) than the vapor compression refrigeration cycle and requires about twice the heat rejection capacity. The input heat required to undertake salt solution regeneration may be provided by solar energy or by relatively high-temperature waste heat from an industrial-type process or a fuel cell. Because high-quality energy (electricity) is replaced by lower-quality heat, the absorption cycle can enjoy an exergy advantage over the vapor compression cycle, even though it is inherently less efficient.

There are several variations on the absorption cycle. When a combustion fuel such as natural gas is used to provide heat for the generator, the process is termed *direct fired*. When a non-combustion heat source (such as waste heat) is used, the process is termed *indirect fired*. Figure 12.33 shows a relatively simple *single-effect* absorption cycle that uses one heat exchanger between the strong and weak salt solutions. A *double-effect* absorption cycle (powered by steam in Fig. 12.34) adds a second generator and condenser that operate at a higher temperature. It approximately doubles the COP of the single-effect cycle. A *triple-effect* cycle, in turn, provides a 50% COP improvement over the double-effect cycle.

A single-effect, indirect-fired absorption chiller (Fig. 12.35) is attractive where central steam or high-temperature water (from solar collectors, waste heat from an industrial process, or outflow from a fuel cell, etc.) is available. Absorption equipment is less efficient than compressive refrigeration cycle equipment, although a cheap or even free heat source to power the cycle can rapidly overcome efficiency disadvantages. Natural gas and absorption refrigeration have often proven cost-effective alternatives to electrically driven vapor compression systems. Absorption machines have fewer moving parts (and therefore require less maintenance) and are generally quieter than vapor compression equipment of similar capacities. They can be environmentally attractive because they do not use CFCs or HCFCs and because they require far less



1 *Evaporator and absorber*
Consider two connected, closed tanks with a salt solution (lithium bromide) in one and water in the other. Just as common table salt absorbs water on a damp day, the salt solution in the absorber soaks up some of the water in the evaporator. The water remaining is thereby cooled by evaporation.

2 *Evaporator coil and pump added*
This refrigeration effect is utilized by putting a coil in the evaporator tank. Water from this tank is pumped to a spray header which wets the coil. The spray's evaporation chills water in the coil as it circulates to the refrigeration load. Solution pumped to spray in absorber raises efficiency.

3 *Solution pumps and generator added*
In an actual operating cycle, the salt solution is continuously absorbing water vapor. To keep the salt solution at the proper concentration, part of it is pumped directly to a generator where excess water vapor is boiled off. The reconcentrated salt solution is returned to the absorber tank, where it mixes with the solution sprayed to absorber in step 2.

4 *Condenser and heat exchanger added*
Water vapor boiled off from the weak solution is condensed and returned to the evaporator. A heat exchanger uses the hot, concentrated salt solution, leaving the generator to preheat the cooler, weak solution coming from the absorber. Finally, condensing water circulating through the absorber and condenser coils removes the waste heat.

Fig. 12.33 A single-effect *absorption refrigeration cycle. The refrigeration capacity from this cycle (step 4) is embodied in a chilled water supply system. The heat source for the generator can be* indirect fired *(steam, hot water, waste heat, or solar energy) or* direct fired *(natural gas). (Adapted courtesy of the Carrier Corporation.)*

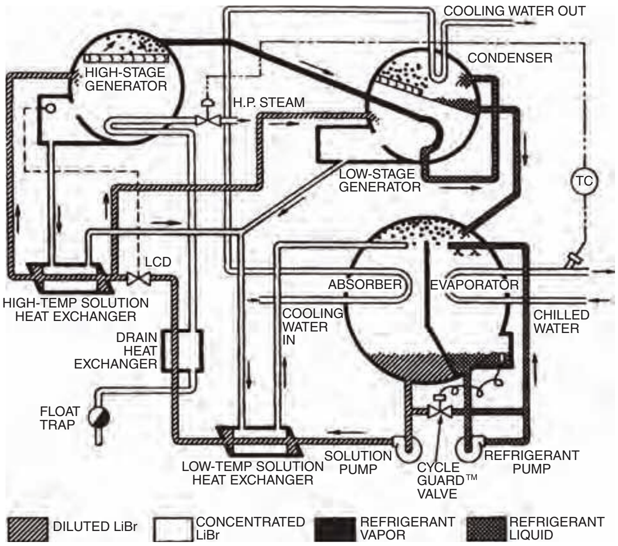


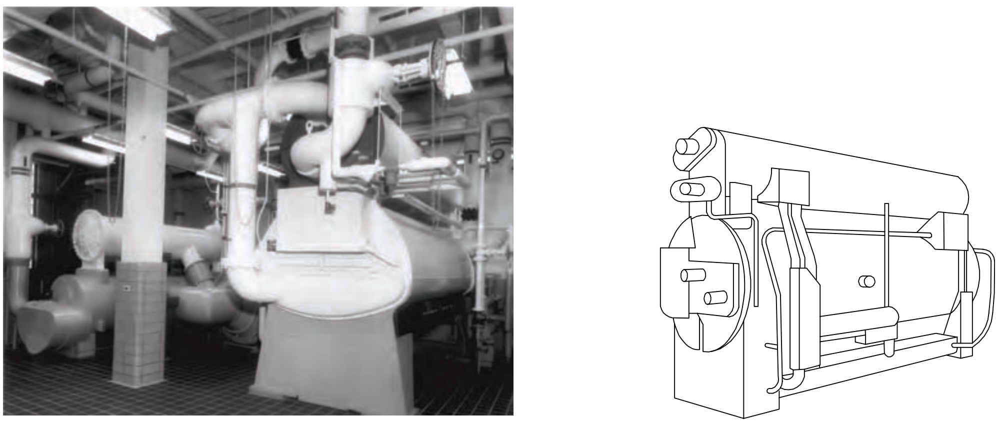
Fig. 12.34 *Indirect-fired double-effect absorption cycle. Lithium bromide and water are used as refrigerants. (Courtesy of the Carrier Corporation.)*

electricity to operate. The higher waste heat output of about 31,000 Btu/ton (9299 kJ/kW), compared to at most 15,000 Btu/ton (4499 kJ/kW) for compressive cycle equipment, is a design consideration. Absorption refrigeration is almost always employed in a chiller configuration—to produce chilled water.

(c) Air-Cooled Condensers

Small-capacity refrigeration systems often employ an air-cooled condenser by which heat removed from a building is dumped to the outdoor environment. These types of condensers pass refrigerant gas through a coil over which outdoor air flows. The temperature of the refrigerant is higher than that of the outdoor air so that heat flows from the refrigerant to the air. This heat loss allows the refrigerant to change state or condense (from the gaseous phase to the liquid phase) while lowering its heat content.

The most common coil type is a fin and tube arrangement. Heat exchange is sensible (involving only temperature difference). Propeller fans



(*a*) (*b*)

Fig. 12.35 *(a) An absorption chiller driven by heat. (The Carrier Corporation; courtesy of Ingersoll-Rand.) (b) Two-stage absorption chiller utilizing steam, producing 200 to 800 tons (700–2800 kW) of cooling. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

are very common in small- to medium-capacity condensers, and are employed to allow forced convection heat exchange. Vertical and horizontal airflow patterns may be found in various equipment models. Airflow quantities of 600 to 1200 cfm/ton (80–160 L/s per kW) are common, and fan power requirements generally range from 0.1 to 0.2 hp/ton (20–40 W/kw). Figures 12.70 and 12.88 show the role of an air-cooled condenser in a typical refrigeration cycle.

(d) Water-Cooled Condensers

Chillers often (but not always) employ a water-cooled condenser connected to a cooling tower to reject the heat that is removed from the chilled water system.

The place of a cooling tower within the overall refrigeration system layout is shown in Fig. 12.9b. More specific detail regarding cooling tower sizes and types is given in Figs. 12.36 and 12.37. Cooling towers are designed to maximize the surface area contact between outdoor air and the condenser water in order to maximize evaporation (and thus heat transfer). In crossflow towers, fans move air horizontally through water droplets and wet layers of fill (or packing); in counterflow towers (prevalent in larger buildings), fans move the air up as the water moves down.

Cooling towers create a special—and unpleasant—microclimate. They move huge quantities of outdoor air (up to 300 cfm per ton [142 L/s per kW]), which they make considerably more humid. In cold weather, they can produce fog. They are typically very noisy—a natural consequence of forced-air motion. The condensing water flows are about 2.8 gpm (0.18 L/s) per ton of compressive refrigeration and about 3.5 gpm (0.22 L/s) per ton of absorption refrigeration.

Between 1.6 and 2.0 gph (1.7 and 2.1 mL/s) of water leaves a typical cooling tower as vapor. This water must be replaced, which is done automatically. The steady evaporation and exposure to the outdoor environment under hot and humid conditions spell trouble for the condensing water: Controls for scaling, corrosion, and bacterial and algae growth are especially important. Ozone treatment systems have the advantage of reliable biological control and leave no chemical residue. Since the discovery of the link between Legionnaires' disease and cooling towers, biological control has assumed greater importance.

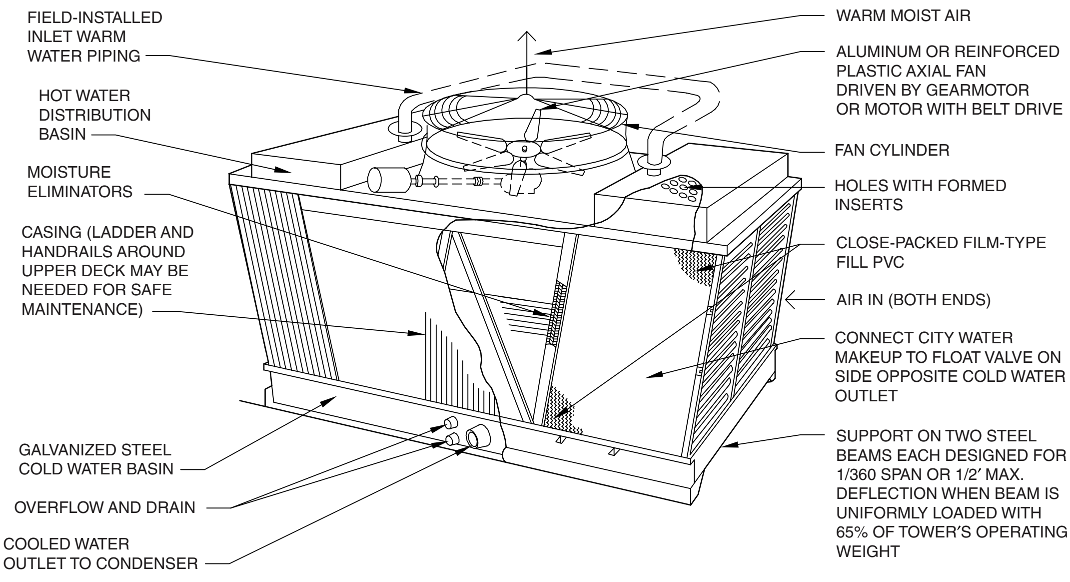
The water vapor that discharges from a cooling tower should be kept from the vicinity of fresh air intakes, and away from neighboring buildings or parked cars, where feasible. The footprint requirements for a cooling tower can be approximated from Fig. 12.7. Alternatively, during schematic design, consider a typical space requirement of 1/500 of the building gross floor area (for towers up to 8 ft [2.4 m] high) or 1/400 of the building gross floor area for higher towers.

Although it is tempting to try to block the noise produced by a cooling tower with solid barriers, it is critical that noise control not interfere with air circulation. The manufacturer's recommended clearances to solid objects adjacent to cooling towers must be consulted before a tower is enclosed in any way. The roof is thus a favorite location for cooling towers, where wind can disperse the water vapor, noise and odor are remote from the street, and aesthetics are less of a concern. A cooling tower can, however, become a design feature; near downtown Denver, the cooling tower for a large performing arts complex sits in a forlorn stretch of grass bordered by arterial streets and away from pedestrians (Fig. 12.38). Its plume adds visual interest as it twists ghostlike above the equipment.

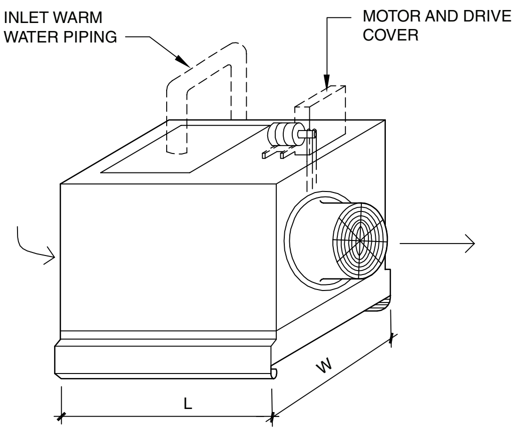
When fouling of the condensing water system cannot be tolerated, an alternative approach using a *closed-circuit evaporative cooler* may be considered. Its schematic operation is described in Fig. 12.39. Usually used to cool refrigerant directly, it can also be used to cool condenser water, as well as being used in water-loop heat pump systems. The refrigerant or condenser water is protected within an always-closed loop, while a separate body of water is recirculated through the cooler, with steady evaporation and its attendant problems. This type of device requires much less makeup water than a cooling tower.

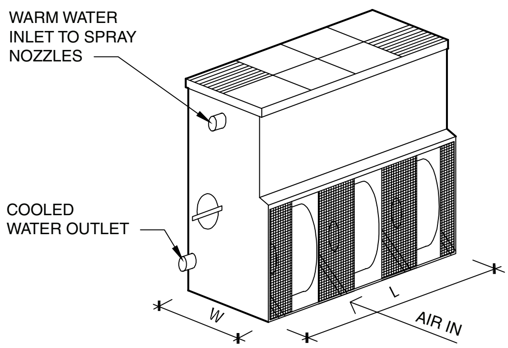
(e) Heat Pumps

Discussion of heat pumps brings knowledge of the vapor compression refrigeration cycle and condensing equipment into play. A heat pump



(*a*)





COOLING TONS	OVERALL DIMENSIONS (IN.)			OPERATING WEIGHT (LB)	MOTOR (HP)
	L	W	HT.		
5	69	33	60	940	1/4
25	75	45	80	1600	1
50	84	64	92	2500	3
100	93	100	92	4200	5
150	100	144	112	8000	7-1/2

(*b*)

COOLING TONS	OVERALL DIMENSIONS (IN.)			OPERATING WEIGHT (LB)	MOTOR (HP)
	L	W	HT.		
20	36	36	78	950	2
50	72	36	96	1700	7-1/2
150	144	56	122	4800	20
400	140	118	192	14,000	50

(*c*)

Fig. 12.36 *Cooling towers for large buildings. (a) Cutaway view of a large-capacity (200 to 700 ton [700-2460 kW]) crossflow induced-draft package cooling tower. (b) Size ranges for crossflow induced-draft package cooling towers. (c) Size ranges for counterflow induced-draft package cooling towers. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

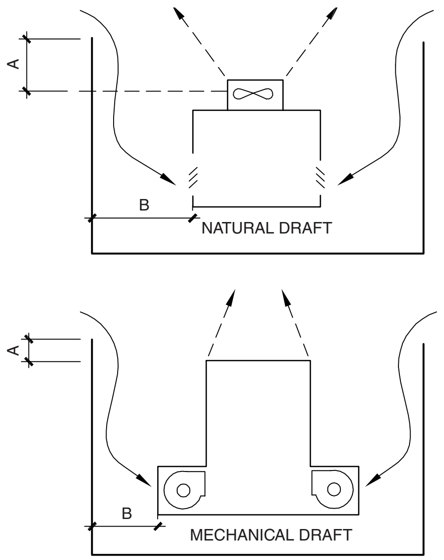


Fig. 12.37 *The more clearance for airflow, the better the operation of a cooling tower. A = maximum height of enclosure above the tower outlet; minimize this dimension. B should be as large as possible, especially if the walls have no air openings. Consult manufacturers for optimum dimensions. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

uses the refrigeration cycle to both heat *and* cool; in an HVAC system it is thus both a heat source component and a coolth source component. As shown in Fig. 12.40, heat is transferred ("pumped") from indoors to outdoors in summer (Fig. 12.40*a*) and from outdoors to indoors in winter (Fig. 12.40*b*). Heat pumps can be configured in air–air, air–water, and water–water arrangements, providing substantial flexibility for a building designer. The most common configuration for small buildings is the air–air heat pump, shown in Figs. 12.40 and 12.41. In a *single-package* (also called *unitary*) system (Fig. 12.41*a*), only one piece of equipment is involved. A single-package air–air heat pump moves heat between an outdoor air stream and an indoor air stream; although kept separate, both streams pass through a *single* enclosure assembly. A system with both outside and inside components is called a *split* system (Fig. 12.41*b*). A split-system air–air heat pump moves heat via a refrigerant loop between the outdoor unit (which also contains the compressor), and the indoor unit. The indoor unit has provisions for the treatment and circulation of indoor air and usually contains a backup heating coil for cold weather conditions that reduce the unit's heat-pumping capacity.

Single-package heat pumps are commonly located on roofs, where they have ready access to outdoor air (the device's heat sink and heat source), and where their noise is less likely to annoy—provided they are adequately isolated from the building structure. This approach is shown in the daylit, passively solar-heated Mount Airy, North Carolina, library (Fig. 12.42). This 14,000-ft^2 (1300-m^2) building also has a solar preheating system for its hot water. The five air–air heat pumps utilize economizer cycles (up to 100% outdoor air when temperatures are favorable). The average annual building energy consumption has been monitored at about 17,000 Btu/ft^2 (53,635 W/m^2)—approximately one-third of nearby buildings with similar functions.

Split-system heat pumps are popular because the noise of the compressor and the outdoor air fan are removed from the interior, and the size of the indoor unit can be quite small. As the distance between the indoor and outdoor units increases, so does the strain on the refrigerant loop. The indoor element is often mounted either high on the wall or on the ceiling. Indoor units are available with automatically changing louvers; when in the cooling mode, cool air is delivered along the ceiling, from where it sinks to the level of occupancy; cold air blowing directly on people is avoided. In the heating mode, the louvers shift to direct hot air steeply downward.

One of the primary attractions of a heat pump is that in the heating mode it can deliver more energy than it consumes (as electricity). Although electricity is required to run the cycle, the heat pump draws "free" heat from a source such as outdoor air. The total heat delivered to the building is substantially more than the heat equivalent of the electricity required to run the cycle. The measure of this heat advantage is called the *coefficient of performance* (COP), which was defined in Section 12.4(d).

Because performance for a given piece of equipment changes with varying outdoor conditions and with indoor loads, a *seasonal energy efficiency ratio* (SEER) rating metric has been established. SEER expresses the Btu/h removed for each

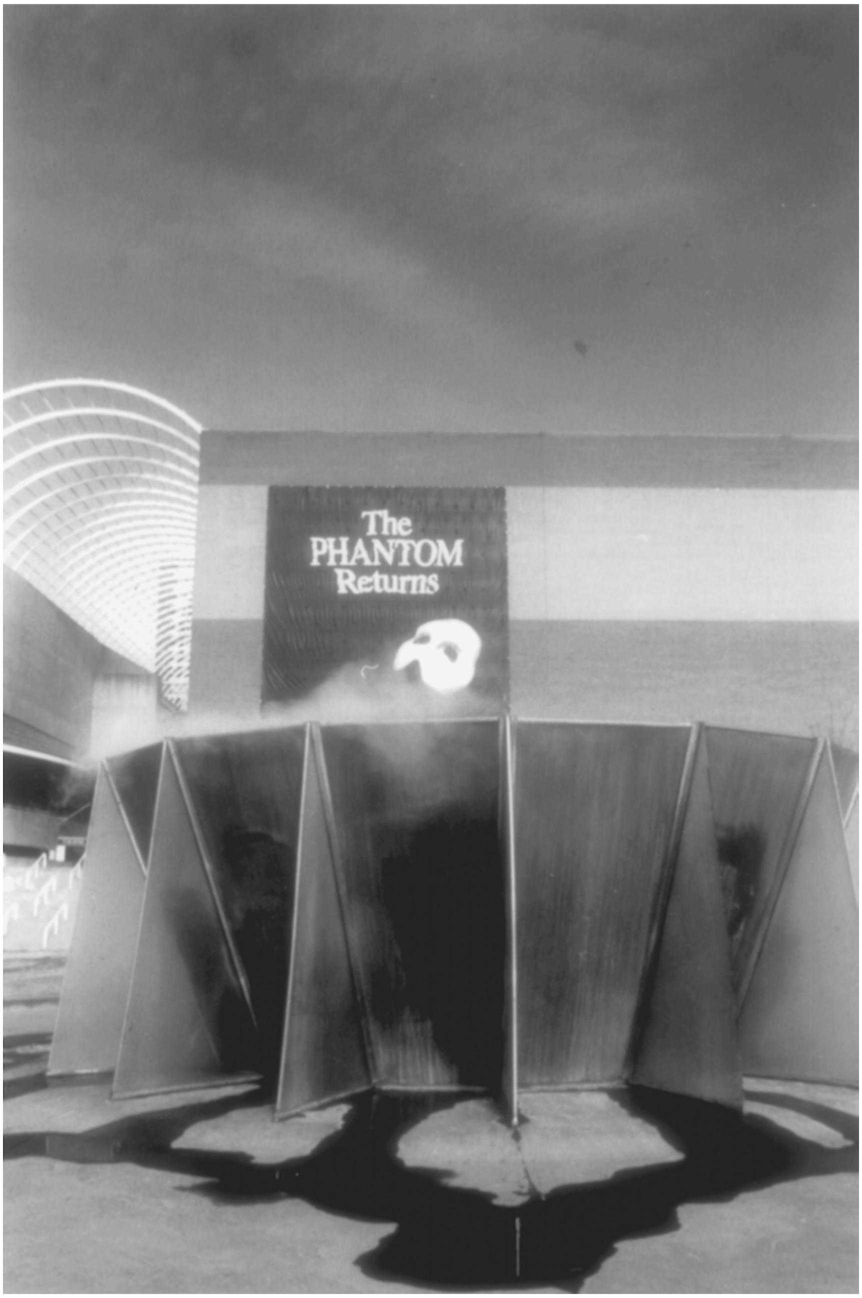


Fig. 12.38 *A plume of mist hovers ghostlike above a cooling tower in full public view near the Denver performing arts complex.*

watt of energy input, averaged over the cooling season. The higher the SEER, the more efficient the heat pump's seasonal performance. SEER ratings range as low as 5 and as high as 15. A similar rating metric has been developed for the heating cycle of a heat pump; this is called the *heating seasonal performance factor* (HSPF).

As might be expected from a device that draws heat from the outdoor air in winter, there are limitations to a heat pump's heating performance. As outdoor temperatures approach 32°F (0°C), the COP drops, and the outdoor coil tends to ice over. Backup electric resistance heating must then be used, which ends the efficiency advantage that

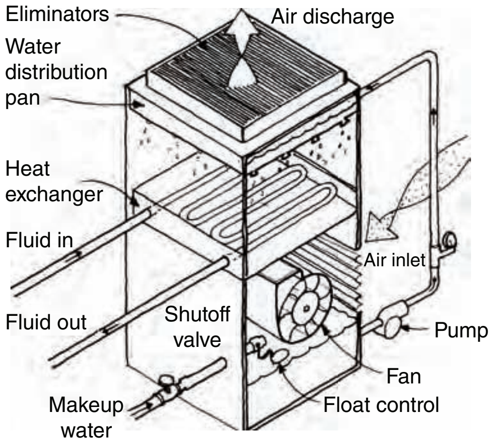


Fig. 12.39 *Closed-circuit evaporative coolers cool a condensing water system while protecting it from contact with outdoor air. A self-contained water system is circulated through the evaporative cooler; steady evaporation losses are replaced by makeup water. (Based upon AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *8th ed.; © 1988 by John Wiley & Sons.)*

made the heat pump attractive. See Fig. 12.43 for a demonstration of falling performance with falling temperatures. Because of this characteristic, air–air heat pumps are not commonly used in cold-winter climates. Air–air heat pumps are a questionable backup system for a passively solar-heated building in a cold climate, because backup sources are typically needed only in the coldest weather.

Heat pumps that transfer heat from *water* sources (such as wells or solar-heated storage tanks) or from the *ground* perform much more dependably and efficiently in cold weather. Water–air heat pumps (shown in Fig. 12.40*c*) and solar collectors make an effective team. As a high-COP heat pump removes heat from the solar storage tank (for delivery to the indoor air), the resulting lower temperature of the solar-heated water *increases* the solar collector's performance. Assume that on a cold, partly sunny day, the collector is fed water from the tank at 90°F and is able to raise its temperature by 4F° to 94°F (from 32° to 35°C). This improvement is slight because of the rather high heat loss that a 94°F collector experiences when surrounded by cold air. If, however, the collector were to be fed 59°F (15°C) water, its heat loss would be greatly reduced. The heat that the collector *does not* lose to the cold air can be invested in the 59°F water, which will thus leave at a considerably

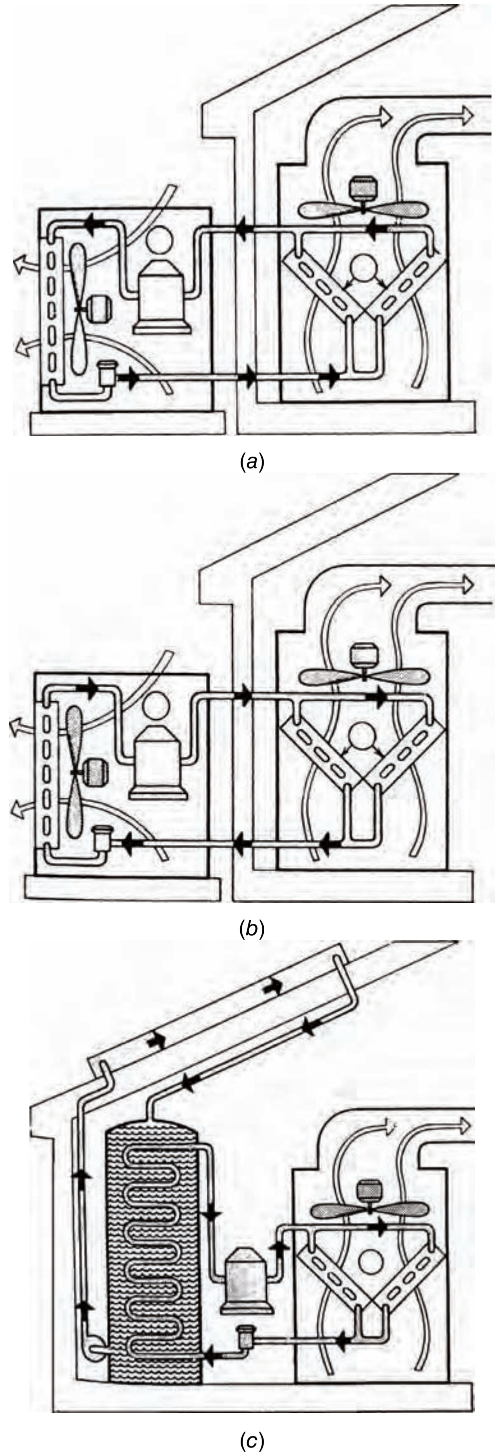
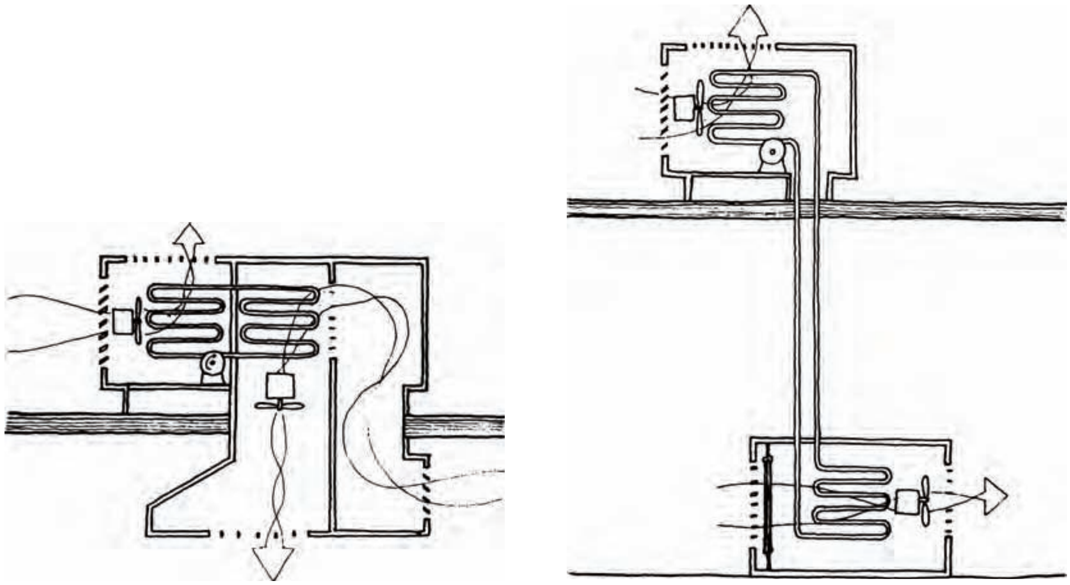


Fig. 12.40 *Heat pump applications. A simple air–air heat pump provides space cooling (a) or space heating (b). Teamed with a solar collector and water storage tank (c), the heat pump can yield usefully warm temperatures in the air stream while increasing the collector efficiency by lowering the storage tank temperature. (Reprinted with permission from* Popular Science; *© 1978 by Times Mirror Magazines, Inc.)*



(*a*) (*b*)

Fig. 12.41 *The package unit (a) and the split system (b) are popular applications of the air–air heat pump. The package unit and the outdoor unit of the split system are also typically placed either on the ground or on a roof (as shown here).*

higher temperature of 59 + 4 = 63°F (17.2°C). Thus, more solar energy is collected, and more is available for transfer to the building via the heat pump. The heat pump, in turn, can heat the 59°F tank water to much higher temperatures to serve the building's heating needs.

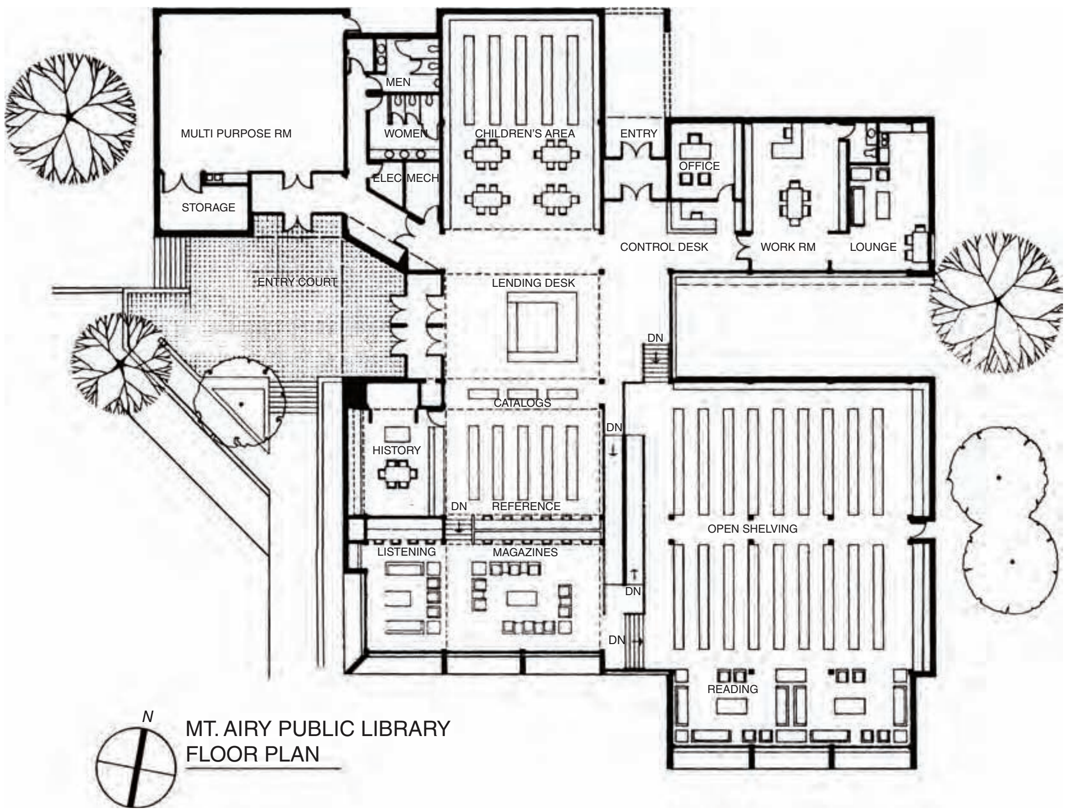
Most heat pumps utilize electricity to drive the vapor compression refrigeration cycle; there are, however, absorption cycle heat pumps that utilize natural gas. The *GAX heat pump* (championed for some time by Oak Ridge National Laboratory and shown in Fig. 12.44) not only uses natural gas for heating and cooling, it has no CFCs or HCFCs and functions at outdoor temperatures much lower than those of an electric air–air heat pump. Eventually, solar energy may be used to drive the absorption cycle. Solar-driven refrigeration is a particularly elegant blend of energy source and task—the hotter the sun, the greater the cooling capacity.

Ground-source heat pumps: Also often (but inaccurately) called geothermal heat pumps or Geo Exchange systems. These are found in several configurations. They often provide domestic hot water in addition to heating and cooling. An environmentally safe heat exchange fluid is circulated through a loop installed underground (or in a pond or lake), taking heat from the soil in winter and discharging heat to the soil in summer. The loop is often constructed of high-density polyethylene (HDPE). Soil temperatures below the surface are more stable year-round than outdoor air temperatures; tapping into this more benign environment raises the system COP relative to that of air–air heat pumps. The outdoor portion of this system is almost completely out of sight, with no maintenance or weathering of exterior equipment. Noise is confined to the compressor, which can be placed in a small indoor mechanical room.

Some common ground-source configurations are shown in Fig. 12.45. In the closed systems (a–c) the flow rate is typically 2 to 3 gpm/ton of refrigeration (0.3 to 0.5 mL/J), with lower flows in the open-loop systems.

The horizontal closed-loop heat pump (Fig. 12.45*a*) requires trenches 3 to 6 ft (1 to 2 m) deep; typically, 400 to 650 ft (120 to 200 m) of pipe are installed per ton (12,000 Btu/h or 3.5 kW) of heating and cooling capacity. To squeeze more pipe length into a trench, a "slinky" coiled pipe is sometimes used. The trenches can be placed below parking lots or lawns and gardens.

(*a*)



(*b*)

Fig. 12.42 *Mount Airy Library, Mount Airy, North Carolina. Mazria/Schiff & Associates, Architects. (a) View from the southwest. (Photo by Gordon H. Schenck, Jr.) (b) Plan. (c, d) North–south sections relating sunlight and natural heat flow. Individual package heat pumps are set on the flat-roof sections.*

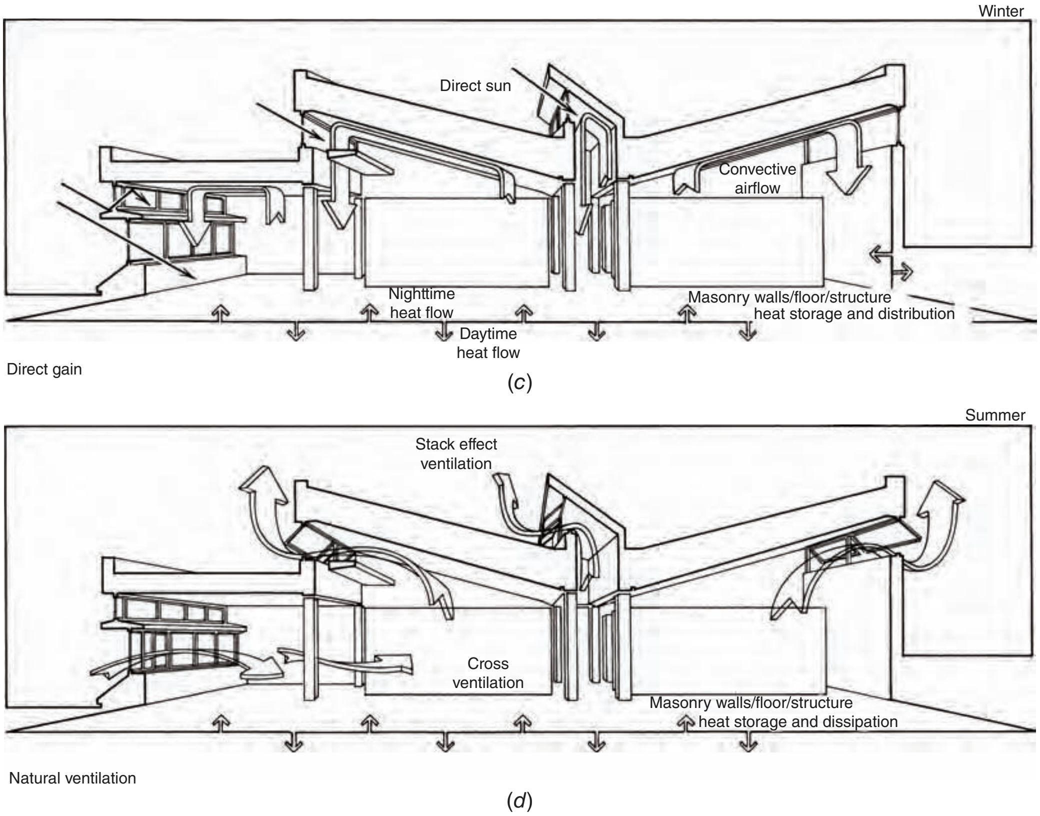


Fig. 12.42 *(Continued)*

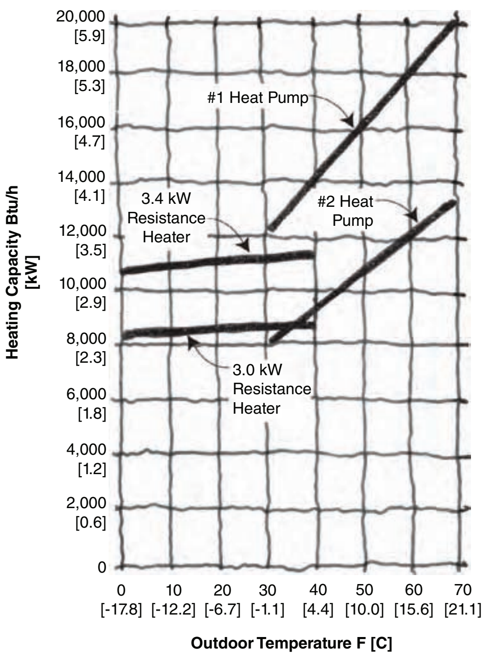


Fig. 12.43 *Typical air–air heat pump operating characteristics. Heat delivery falls with falling outdoor temperature. (Redrawn by Jonathan Meendering.)*

The vertical closed-loop heat pump (Fig. 12.45*b*) is particularly applicable where the site area is limited. Vertical holes are bored from 150 to 450 ft (46 to 137 m) deep. Each hole contains a single full-depth loop and is backfilled (or grouted) after the loop is installed. Because the temperature is more stable at greater depths, less pipe length is required than for horizontal loops. The distance between boreholes varies from a minimum of 15 ft (4.6 m) with high water table and low building cooling loads to as much as 25 ft (7.6 m) for buildings with high cooling loads. A minimum distance of 20 ft (6 m) is usually recommended.

The pond or lake closed-loop heat pump (Fig. 12.45*c*) is sometimes used when a building is close to an adequately large body of water. The loop is submerged, and the surrounding water conducts heat far more rapidly than does soil. The resulting shorter loop length, and the low cost of placing the coils in water, can make this attractive. However, the water level in the pond should never drop below a minimum of 8 ft (2.5 m) and must have sufficient surface area for heat exchange.

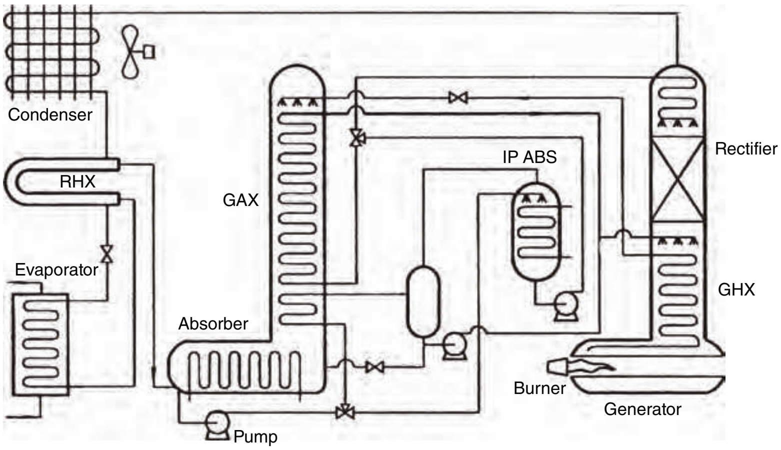


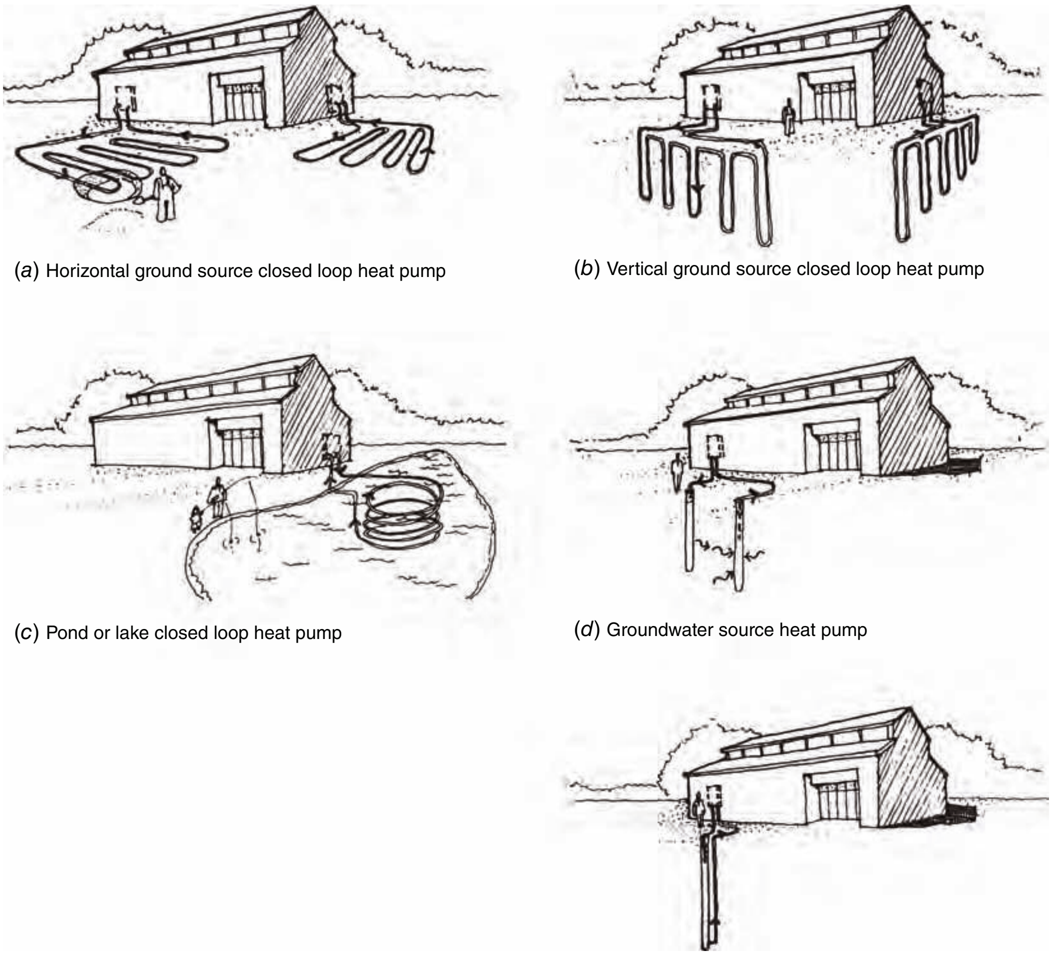
Fig. 12.44 *An air-cooled advanced GAX (generator-absorber heat exchange) heat pump uses aqua ammonia as the absorbent and is operational down to −10°F (−23°C). The target cooling COP is 0.95; heating COP is 1.55. Designed for light commercial applications, it ranges from 5 to 25 tons capacity. (RHX = refrigerant heat exchanger; IP ABS = intermediate pressure absorber; GHX generator heat exchanger.) (Courtesy of Energy Concepts Company, Annapolis, MD.)*

The groundwater-source open-loop heat pump ("pump and dump") is suitable only where groundwater is plentiful, and may be prohibited by local codes and environmental regulators. One variant of this system (Fig. 12.45*d*) takes water from one well, through a heat exchanger within the building, then discharges it to a second well. Another variant (Fig. 12.45*e*) takes water from the bottom and discharges back into the top of the same (standing) well, typically 6 in. (150 mm) in diameter and as deep as 1500 ft (460 m).

The Wildlife Center of Virginia at Waynesboro is a wildlife teaching–research hospital. Its 5700-ft^2 (530-m^2) floor area is served by four ground-source heat pumps (two at 4 tons, two at 5 tons) connected to 11,350 ft (3460 m) of underground horizontal pipe, laid in a "slinky" configuration and thus fitting within about 2500 ft (760 m) of trench. The trench was dug around existing trees and placed under future roadways in a forest setting. Energy simulations estimated that annual heating, cooling, and hot water use would be about 35,000 kWh. Had air–air heat pumps and an electric water heater been used instead, the estimate was 66,000 kWh—with a 47% yearly savings advantage for the ground-source system.

Ground-source heat pumps are often used in retrofits, especially for schools where site areas are plentiful, or historic structures where small mechanical systems are highly desirable. The Daniel Boone High School near Johnson City, Tennessee, was built in 1971 with a two-pipe chilled water system and electric resistance heat. An ASHRAE Technology Award was given to recognize this 160,000-ft^2 (14,864-m^2) school, which was retrofitted with a ground-source vertical closed-loop heat exchanger fed by 320 boreholes that are 150 ft (46 m) deep. Each borehole loop is 300 ft (91 m) of ¾-in. (19-mm) polyethylene pipe. The boreholes are arranged in sections of 20 holes each. The holes are 15 ft (5 m) on center. The 20-hole sections are separated by 20 ft (6 m). The loops all connect to an 8-in. (203-mm) supply and same-size return line to a new heat exchanger within the existing mechanical room. Within the building, a new water loop heat pump system is installed, one heat pump in each zone.

Water-source heat pumps: The Daniel Boone High School uses an interior closed water loop that connects all the heat pumps serving all thermal zones. This system facilitates heating in one zone while another zone is being cooled, because simultaneous heat "deposits" and heat "withdrawals" actually help the system to function most efficiently. Figure 12.46 diagrams a typical water loop system, where a supplementary heat source (such as a boiler for cold weather) and a supplementary heat rejector (such as a cooling tower for hot weather), are installed to maintain usable water temperatures within the loop across an annual cycle. A large office building in Pittsburgh that uses such a system is shown in Fig. 12.47.



(*a*) Horizontal ground source closed loop heat pump

(*b*) Vertical ground source closed loop heat pump

(*c*) Pond or lake closed loop heat pump

(*d*) Groundwater source heat pump

(*e*) Standing column groundwater-source heat pump

Fig. 12.45 *Configurations of ground-source heat pumps. (a) Horizontal closed loop laid in trenches. (b) Vertical closed loop placed in boreholes. (c) Pond or lake closed loop. (d) Groundwater-source heat pump taking water from one well and discharging it to another. (e) Standing column groundwater-source heat pump taking water from, then discharging to, the same well.*

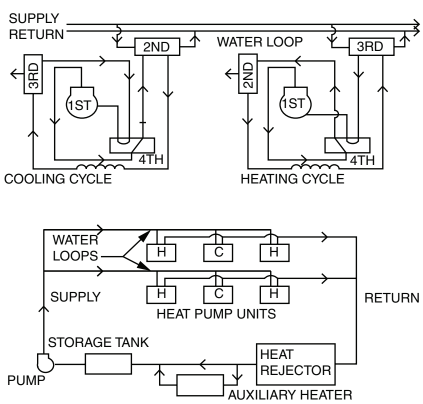
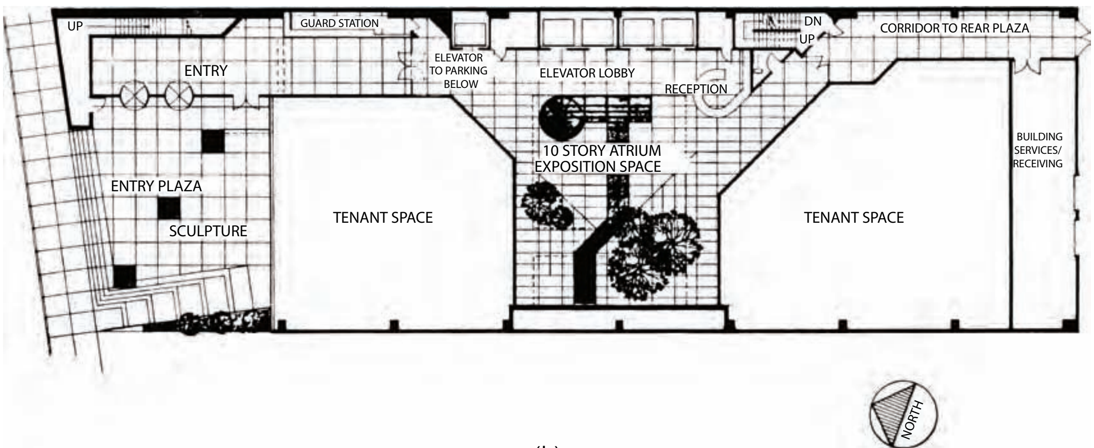


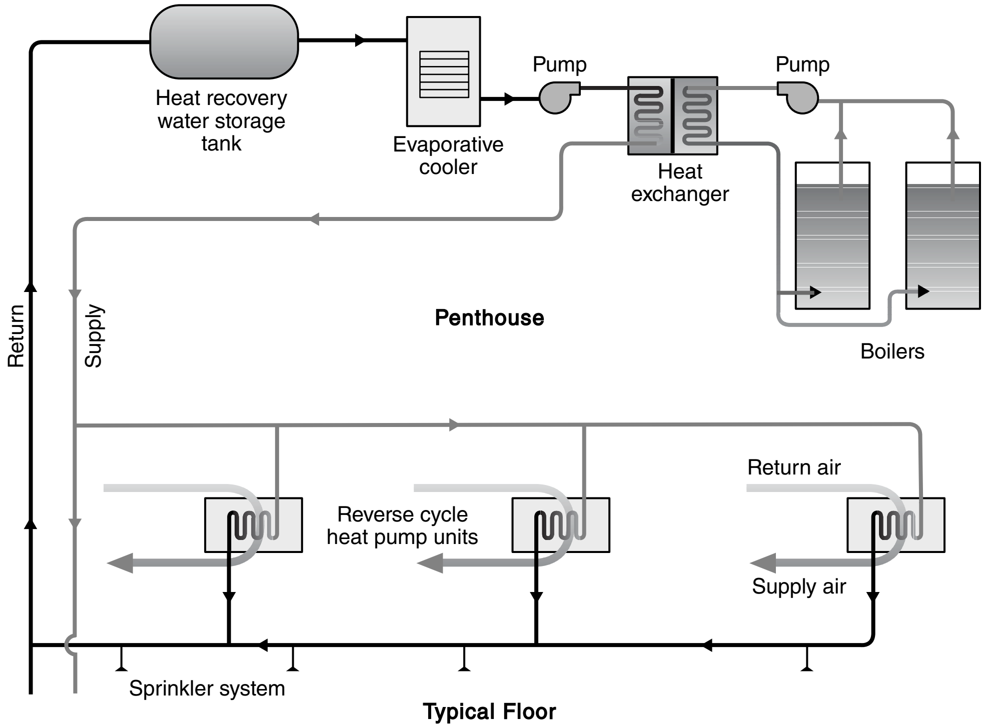
Fig. 12.46 *Water-source heat pumps. (a) An individual water–air heat pump either deposits heat into the loop (while cooling) or withdraws heat (while heating). This system is particularly well suited to buildings where simultaneous heating and cooling needs occur. (b) Supplementary heat sources (boilers) and heat rejectors (cooling towers) are usually provided. (Reprinted by permission from AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 11th ed.; © 2007 by John Wiley & Sons, Inc.)*

(a)

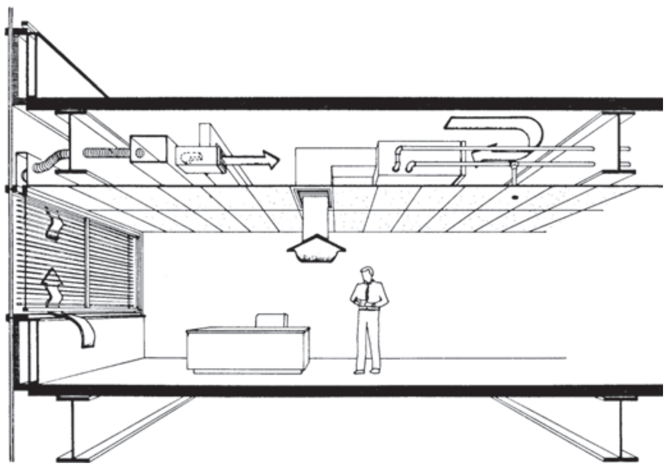


(b)

Fig. 12.47 *The Comstock Center, Pittsburgh, Burt Hill Kosar Rittelmann Associates, architects. (a) The north and west faces. (b) Ground-floor plan. (c) Water loop heat pumps are linked via the sprinkler system on each floor. This is also called a tri-water system. (d) Extract-air windows (see Fig. 12.50) control infiltration and moderate the perimeter zone temperatures. (e) The central daylighting atrium is tempered by exhaust air from the offices; exhaust air then leaves via the stack effect. (f) The stack effect also controls summer overheating.*

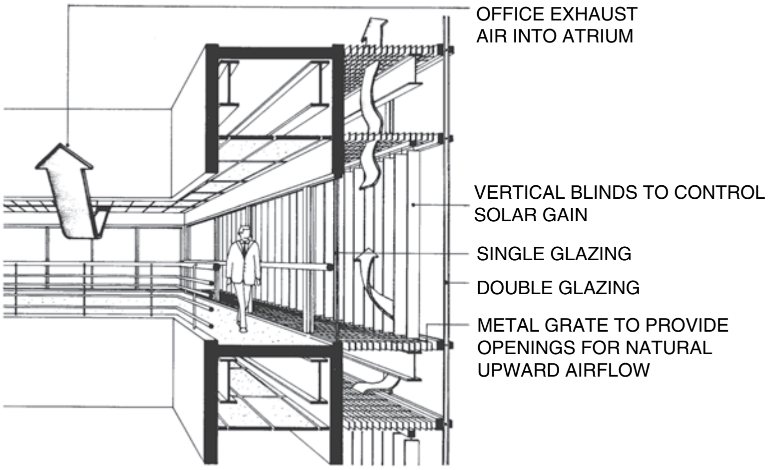


(*c*)

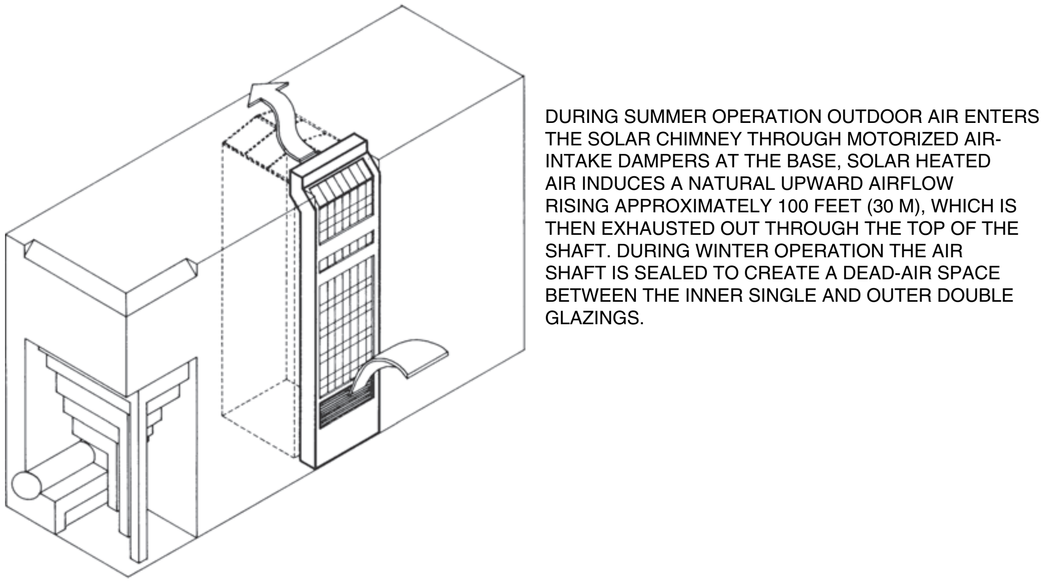


(*d*)

Fig. 12.47 *(Continued)*



(*e*)



(*f*)

Fig. 12.47 *(Continued)*

Water loop heat pumps: This is a special case application of water-source heat pumps. Interconnected heat pumps (water-to-air) draw heat from a common water circulation loop (in heating mode) or discharge heat to the loop (when in cooling mode). For a large building in cold weather, heat removed from the interior zones is used to warm the perimeter zones. The loop's temperature may range between 65° and 90°F (18° and 32°C). In hot weather, a cooling tower disposes of excess heat (not required for heating any zone), whereas in cold weather a central boiler adds needed heat to the water loop. The loop is sized to carry 2 to 3 gpm (0.13 to 0.19 L/s) per ton, where the total tonnage equals the sum of the capacity of all the individual units (often greater than the actual load).

This loop approach is diagrammed in Fig. 12.46 and is used in the school shown in

Fig. 12.51. In the 175,000-ft^2 (16,260-m^2) Comstock Center in Pittsburgh (Fig. 12.47), there are six to eight small heat pumps on each of the 10 floors; these units are located above the suspended ceiling. Their connecting water loop doubles as the building's wet-pipe sprinkler system supply; this is possible because the heat pumps keep the loop between 65° and 85°F (18° and 29°C). Because no additional water distribution piping is needed (beyond the sprinkler piping), there is a substantial first-cost saving, and relatively little building volume is consumed for HVAC distribution elements. A 23,000-gal (87,060-L) water storage tank allows daytime heat, rejected to the loop by the heat pumps, to be stored and recalled for nighttime heating. When necessary, two small boilers maintain the 65°F minimum temperature in the water loop or an evaporative condenser holds maximum temperature at 85°F.

In addition to the innovative use of the sprinkler piping loop, the Comstock Center uses air-extract windows (see Fig. 12.53) to control infiltration and to moderate the perimeter zone temperatures. After return air passes up inside this window and arrives in the ceiling plenum, it is mixed with fresh air, then tempered and recirculated by the air side of the heat pumps. The Comstock Center also utilizes a large daylighting atrium, whose temperature control is provided largely by exhaust air from the offices; the stack effect is utilized to provide natural ventilation on its west face in summer conditions.

Motels are often good candidates for water loop heat pumps, because some rooms receive solar radiation while others are shaded; some are occupied, some unoccupied; and there are substantial domestic hot water needs. All these factors combine to make a heat-sharing water loop attractive.

(f) Evaporative Coolers

The third currently-viable active source of coolth is evaporative cooling. This approach to cooling involves a basic psychrometric process (see Section 12.4*d*). Evaporative cooling may, in fact, be achieved through passive means, via a hybrid system (mostly passive with a bit of help from active components), or by means of an active system. Active evaporative cooling employs equipment called an evaporative cooler. A range of evaporative cooling systems is discussed in Section 12.17(c).

12.9 DISTRIBUTION COMPONENTS: AIR

Distribution components connect source components to delivery components in a central HVAC system. (Local systems are close-coupled and have little need for distribution; district systems function as central systems at the building scale.) The building designer faces a fundamental decision regarding the medium that will be used to convey heat and/or coolth effect around a building. Should this medium be air or water? Both will work, both have been used effectively in the past, and both are competing for attention in high-performance buildings—see for example the controversial *ASHRAE Journal* article comparing VAV (air) to chilled beam (water) systems (Stein and Taylor, 2013). Air can be directly introduced into a room, can inherently address indoor air quality concerns, but has very low thermal capacity—requiring large conduits (ducts). Water has the opposite characteristics; it is thermally efficient—permitting small conduits (pipes), but cannot be allowed to flow directly into a room, and does not inherently deal with air quality.

Examples of air-based and water-based systems (including hybrid air–water systems) are discussed in Section 12.18. This section looks at the equipment artifacts associated with air as a distribution medium.

(a) Fans

The purpose of a fan is to circulate (move) air. Buildings may employ stand-alone fans (such as a ceiling fan or industrial exhaust fan), fans that are packaged as a product (such as residential-scale bathroom exhaust fans), fans that are inserted into ductwork (such as an exhaust or return air fan), and fans that are part of a larger equipment item (such as an air-handling unit). Fans may be found in hybrid climate control systems and most certainly will be found in the vast majority of HVAC systems.

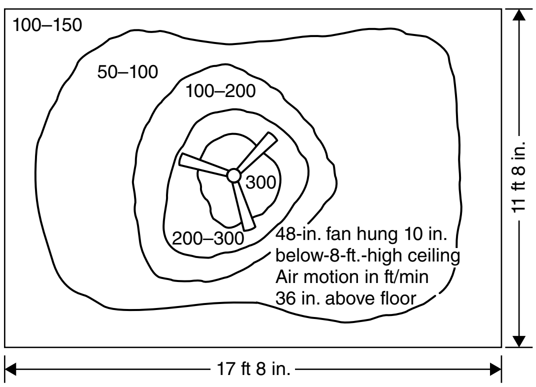
Ceiling fans: Before the advent of HVAC systems, cooling effect was commonly achieved with simple air motion provided by fans. The summer thermal comfort chart shown in Fig. 4.14 encourages increased air motion as a way to extend comfort into air temperatures in the mid-80s °F (roughly 29°C). As a general rule, people will perceive a 1F° decrease in air temperature for every 15 fpm increase in air speed at the body (about a 1C° decrease for every 1 m/s increase). Ceiling fans are often installed to run at slow speed to destratify warm air at the ceiling in winter. They can be run at higher speed in summer to provide added comfort through increased air motion. The air motion produced by ceiling fans will vary with the fan height above the floor, the number of fans in a space, and the fan power, speed, and blade size. Figure 12.48 shows expected air speeds with one 48-in. (1220-mm) ceiling fan in a typical residential living room.

In the hot summer climate of Davis, California, an experimental house (sponsored by Pacific Gas & Electric and designed by the Rocky Mountain Institute) eliminated a conventional cooling system through a series of alternative approaches. Fans play a major role: In addition to ceiling fans, a whole-house fan removes the hottest air from the central hallway, exhausting to the ventilated attic. Increased thermal mass (tile floors, double drywall), an attic radiant barrier, and low-e, gas-filled windows are also used.

Other fans: Manufacturers of packaged HVAC equipment will normally select a fan type and capacity that best suits their product objectives. HVAC engineers, however, will need to select standalone fans and may be able to select from among fan options within packaged equipment selections. Key operational parameters are airflow and static pressure; for a given fan product, these are related through a fan curve. Analysis of fan curves allows a designer to ensure the selection of a fan that will perform well across the range of conditions it will likely encounter in use. The fan affinity laws show that fan power is related to fan airflow via a cubic power relationship. Reductions in airflow result in substantial reductions in power draw—this effect is important to consider in high-performance buildings. Variable frequency drives (VFDs) that can deliver energy savings under reduced flow rates are becoming the norm in all new HVAC systems. For detailed fan information see Chapter 21 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment*. Fan types likely to be encountered in HVAC systems include:

Panel (or propeller). A basic air-moving device. The motor is generally mounted in the center of the propellers. It is not designed to work against substantial static pressure (as will result from pushing air through ductwork, filters, coils). This is a noisy type of fan, most commonly used for the V (ventilation) in HVAC.

Centrifugal. Centrifugal fans are the workhorses of HVAC system air moving. They are often used in air-handling units. With an airfoil blade wheel, a centrifugal fan has high efficiency over a wide operating range and is reasonably quiet. A major change in pressure can result from only minor changes in the volume of airflow.



(*a*)

(*b*)

Fig. 12.48 *Ceiling fans are useful for both heating and cooling. In winter, at slow speeds, they destratify warm air at the ceiling. In summer (a) they extend the comfort zone by providing increased air motion. The illustrated room size is typical of residential living rooms. (Reprinted with permission of ASHRAE from 1997* ASHRAE Handbook—Fundamentals. *This citation to an older version of the* Handbook *is intentional and provides access to historic reference information of ongoing interest.) (b) A ceiling fan is a visual feature in this Oregon residence. (Photo by Nathan Majeski.)*

Fixed pitch vane axial. Common for industrial applications. This fan is capable of working against somewhat more static pressure than a panel fan.

Vane axial adjustable pitch. The blade pitch is adjustable occasionally (not continuously) to provide for system balancing or seasonal changes in airflow volume. This fan requires less space than a centrifugal fan and can work against higher static pressures.

Vane axial controllable pitch. The automatically controlled (real-time) pitch adjustment can respond to changes in system temperature, airflow, pressure, and so on, depending upon the sensors employed. This fan is commonly used in VAV (variable air volume) systems.

(b) Air-Handling Units

An air-handling unit (AHU) is a packaged component that is found in both all-air and air-water HVAC systems. Although AHUs are typically selected from a manufacturer's catalog and delivered to the site as a unit, large HVAC systems may use built-up AHUs that are custom designed and assembled for a given project. Depending upon project needs, an air-handling unit will normally include a fan (to circulate air through the system), a filter (to clean the air and protect the fan and coils), and a cooling coil (when cooling is required). Heating coils are also commonly included with AHUs for a number of system types.

Numerous accessory components are available to meet the needs of specific projects. These may include a humidifier unit (to add moisture to the air, usually of interest during the winter in cold climates); a mixing box (to thoroughly mix outdoor and return air streams for better system performance); plenums of various types (to facilitate transitions in airflow); access doors and panels (to ease maintenance); preheat coils (to temper winter outdoor air intake in a cold climate so as to prevent freezing of the main heating/cooling coils); various types of dampers; and economizer sections (to permit use of unconditioned outdoor air as system supply air).

A residential furnace is a small air-handling unit. The air-handling units in large buildings can be huge. See Fig 12.49 and Table 12.3 for typical installation layouts and dimensions. As with all mechanical and electrical equipment, providing

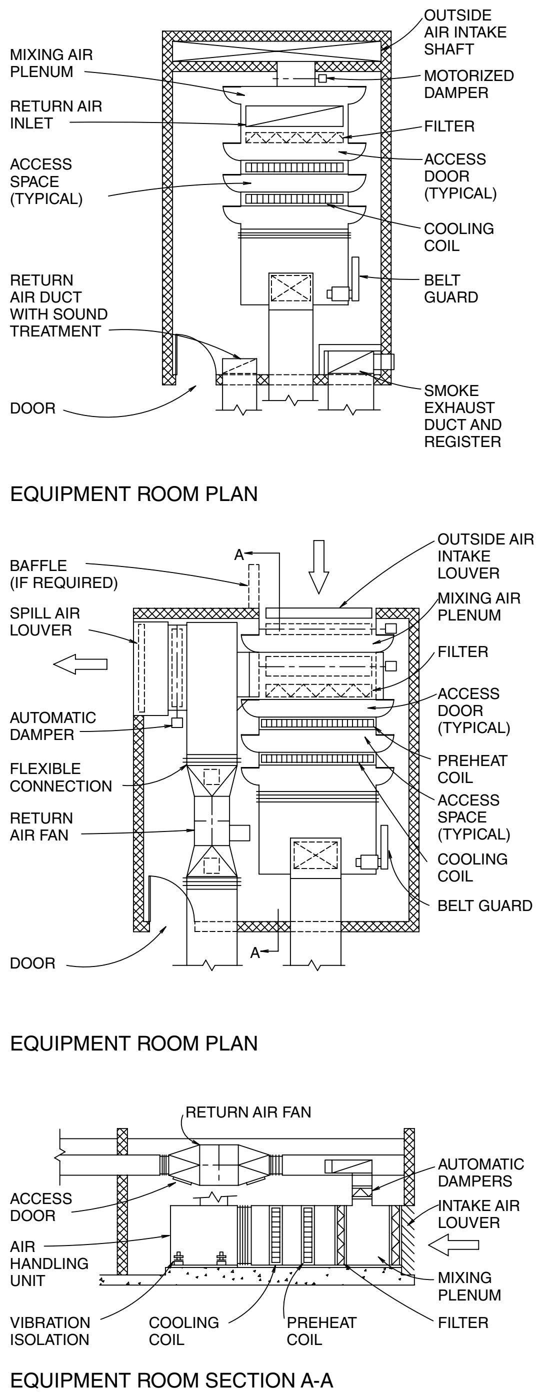


Fig. 12.49 *Some variations on the wide range of HVAC equipment room arrangements. (a) Plan with floor-mounted air-handling unit. Outdoor air is drawn from an adjacent shaft; return air ducts are above the equipment, and a remote exhaust fan expels air that is not recirculated. (b) Plan of air-handling unit on an exterior wall. Outdoor air is taken through the wall, and a return air fan is overhead. (c) Section through plan* b. *(From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *10th ed.; © 2000 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

TABLE 12.3 Air-Handling Equipment Rooms

PART A. I-P UNITS						
	Approximate Overall Dimension of Supply Air Equipment			*Recommended Room Dimensions*		
cfm Range	**Width** ×	**Height** ×	**Length**	**Width** ×	**Height** ×	**Length**
1000–1800	4′–9″	2′–9″	14′–9″	12′–6″	9′–0″	18′–9″
1801–3000	5′–0″	3′–6″	16′–0″	13′–9″	9′–0″	20′–0″
3001–4000	6′–9″	4′–6″	16′–0″	17′–6″	9′–0″	20′–0″
4001–6000	7′–6″	4′–6″	16′–9″	18′–0″	9′–0″	20′–9″
6001–7000	7′–6″	4′–9″	18′–3″	18′–6″	9′–6″	22′–3″
7001–9000	8′–0″	5′–0″	18′–9″	19′–0″	10′–0″	22′–9″
9001–12,000	10′–0″	5′–6″	21′–0″	23′–0″	11′–0″	25′–0″
12,001–16,000	10′–3″	6′–0″	22′–0″	13′–6″	12′–6″	26′–0″
16,001–19,000	10′–6″	6′–6″	23′–9″	24′–0″	13′–0″	27′–9″
19,001–22,000	11′–9″	7′–3″	25′–0″	26′–9″	15′–0″	29′–0″
22,001–27,000	11′–9″	8′–6″	26′–0″	27′–0″	16′–0″	30′–0″
27,001–32,000	13′–0″	9′–9″	27′–9″	29′–0″	18′–0″	31′–9″
PART B. SI UNITS						
	Approximate Overall Dimension of Supply Air Equipment (m)			*Recommended Room Dimensions (m)*		
L/s Range	**Width** ×	**Height** ×	**Length**	**Width** ×	**Height** ×	**Length**
470–849	1.4	0.8	4.5	3.8	2.7	5.7
850–1415	1.5	1.1	4.9	4.2	2.7	6.1
1416–1887	2.1	1.3	4.9	5.3	2.7	6.1
1888–2831	2.3	1.3	5.1	5.5	2.7	6.3
2832–3303	2.4	1.4	5.6	5.6	2.9	6.8
3304–4247	2.4	1.5	5.7	5.8	3.0	6.9
4248–5662	3.0	1.7	6.4	7.0	3.4	7.6
5663–7550	3.1	1.8	6.7	7.2	3.8	7.9
7551–8966	3.2	2.0	7.2	7.3	4.0	8.5
8967–10,381	3.6	2.2	7.6	8.1	4.6	8.8
10,381–12,741	3.6	2.6	7.9	8.2	4.9	9.1
12,742–15,100	4.0	3.0	8.5	8.8	5.5	9.7

Source: AIA: Ramsey/Sleeper, *Architectural Graphic Standards*, 10th ed., © 2000 by John Wiley and Sons. SI conversions added by the authors.

adequate access for regular maintenance, refurbishment, and ultimate replacement is good design practice. Inability to easily reach or work on an AHU can negatively impact its performance and energy efficiency. Manufacturers provide a lot of variety in the air-handling unit product lines: This includes a wide range of cooling, heating, and airflow capacities; units for exterior or for interior installation; and packaged units or built-up units. Whether to place an air-handling unit inside the building envelope (usually in a fan or mechanical room) or outside the envelope (usually on the roof) is worthy of serious consideration—as the decision can substantively impact energy efficiency and maintainability. Chapter 4 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* provides details on building air-handling systems.

(c) Ductwork

Ductwork is the collective name for the air distribution conduits used in HVAC systems. Ductwork may be steel (or other metal), rigid glass fiber, flexible, or cloth. The first three materials are by far the most common. Duct shapes may be round, square, rectangular, or flat oval. In large buildings, ductwork can be physically large and spatially extensive. Coordination of ductwork with other building elements can be a challenge. Ductwork will be large in an all-air HVAC system, substantially smaller in an air–water system, and essentially nonexistent in an all-water or local system. See Chapter 19 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* for details on duct construction. Duct design (sizing and layout) is presented in Chapter 21 of the 2013 *ASHRAE Handbook—Fundamentals.*

Ductwork may contain supply air (in transit from an air-handling unit to the terminal and/or delivery devices within the zones); return air (being recycled from a zone back to the AHU); outdoor air (being brought into a building to assist with IAQ); exhaust air (being channeled out of a building for IAQ or pressure-balance purposes); and/or relief air (return air that is not currently needed for system balance and is being conducted to the outdoors). An all-air system will typically require parallel but separate supply and return air ducts going to/from the various zones. At any point in a building, the supply and return ducts are roughly equal in area. In an air–water HVAC system, there is normally no return air (and thus, no return air ductwork). When there is return air, it is often channeled back to the AHU via a plenum (enclosed architectural volume) rather than a self-contained conduit.

Design considerations for ductwork include:

- Pressure loss: The pressure loss (or drop) in a ductwork system can exert a major influence on system energy efficiency. Resistance to airflow in a ductwork system must be overcome by energy input via a fan. Key areas of pressure loss in a system include air filters, cooling and heating coils, ductwork and fittings, terminal devices, and delivery devices. Of these, ductwork losses are most amenable to reduction through integrated architectural and engineering design. High-velocity airflow will increase friction losses, long ductwork will increase friction losses, and convoluted ductwork will increase friction losses. From an architectural design perspective, ductwork should be kept reasonably short by selecting good fan room locations, and space/volume constraints that result from poor planning should not force the use of too-small ducts that result in high-velocity airflow. ASHRAE Standard 90.1 sets upper limits on fan system horsepower that are directly related to system airflow rate.
- Insulation: Supply air ductwork may need to be thermally insulated (as much to prevent condensation as to reduce heat gains to the supply air); thermal insulation becomes critical when ductwork is run outside of the conditioned envelope of the building (a practice that is generally frowned upon—but addressed by ASHRAE Standard 90.1). Internal insulation (placed inside the ductwork) can act as both thermal insulation and sound-absorbing liner; external insulation will have no effect on ductborne noise transmission. External insulation for condensation control will require a vapor retarder. The thickness of insulation must be considered when squeezing ductwork into tight places.
- Noise control: Control of ductborne noise is often a challenge in many building types. The unbroken path established to lead air from air-handling unit to occupied space transmits sound as readily as air. Mitigation of ductborne noise is a technical design concern addressed in Chapter 48 of the 2013 *ASHRAE Handbook—Applications*. It is important to note that very logical noise control design moves (such as adding complexity to the ductwork layout) may act counter to energy-efficiency design moves.
- Fire protection: Ductwork that penetrates fire-rated assemblies will need to be outfitted with fire dampers. Unnecessary damper installations (caused by uncoordinated design) can add to the cost of a building. The National Fire Protection Association (NFPA) is the definitive North American source for fire protection requirements related to HVAC systems.
- IAQ: Building indoor air quality should be considered as ductwork systems are designed and constructed. Ductwork is generally dark, may be dusty, and may be humid. These are ideal environmental conditions for the development of mold and mildew. The initial cleanliness of ductwork and the ability to maintain such cleanliness over time should be considered by the design team. The *Indoor Air Quality Guide* (ASHRAE, 2009) provides design, construction, and operation information that addresses ductwork and IAQ.
- Approximate sizing: It is often very useful to have an estimate of duct size early in the design process. Duct sizes can influence floor-to-floor heights, structural element dimensions, and the area to be allocated for vertical chases. Approximate sizing can be easily accomplished. Figure 12.8 provides a graphic tool by which to

estimate duct sizes on the basis of building floor area. For preliminary estimates, assuming 1 cfm of airflow per ft^2 (5 L/s per m^2) of conditioned floor area (adjustable up or down to accommodate dense occupancies/unusual loads or energy efficient design) and a velocity of 1000 fpm (5 m/s) (also adjustable as appropriate) allows simple rough sizing of main and branch ducts. The following discussion provides an example of this type of approximation.

1. Determine the quantity of air to be distributed through the duct element of interest. This value can be found from Fig. 12.8, from an estimation of room air change rate (in ACH), or from an airflow/unit area estimation.
2. Express the airflow in cfm (L/s).
3. Establish a maximum velocity (fpm or L/s) for airflow within the duct; this can come from Table 12.4 or be set more arbitrarily (such as 1000 fpm [5 m/s] for larger ducts).

   The approximate *minimum* required cross-sectional area of duct *A* is then

$$A = \left(\frac{\text{volume of air (cfm)}}{\text{velocity (fpm)}}\right) \times \text{friction allowance}$$

where *A* is in ft^2 and the friction allowances are as follows

$$\left[\text{in SI: } A = \left(\frac{\text{volume of air (L/s)}}{\text{velocity (m/s)}}\right) \times 1000 \times \text{friction allowance}\right]$$

where *A* is in m^2 and the friction allowances are as follows

round ducts = 1.0 (may be neglected)
nearly square ducts (ratio of width to depth, 1:1)
small (<1000 cfm [470 L/s]) = 1.10
large (>1000 cfm [470 L/s]) = 1.05
thin rectangular ducts (ratio of width to depth, 1:5) = 1.25

Remember that providing only the *minimum* duct area will carry a penalty of increased noise and pressure loss. Extremely flattened duct cross sections (with width much greater than depth) may be architecturally appealing, but will increase pressure losses due to increased surface area.

Accessories: A number of accessories will be included in a ductwork system to facilitate control, improve performance, and/or increase safety. These devices might include: fire dampers (to close off a duct with a fire rated barrier in the event of a fire); control dampers (to change or redirect airflow); smoke detectors; temperature sensors; pressure sensors; and the like. Consider how such devices might be accessed for maintenance and/or calibration once the building has been closed in.

12.10 DISTRIBUTION COMPONENTS: WATER

When water is employed as a distribution medium in a central or district HVAC system, duct sizes will be substantially reduced (in air–water systems) or ductwork will be eliminated (in all-water systems). This outcome is a result of the much, much higher thermal capacity of water versus air (by about a 3000:1 ratio). The piping systems that convey heat or coolth in an HVAC system are pressurized, of reasonably small diameter, and usually easily coordinated with other building systems. HVAC piping will usually be insulated—both to reduce unwanted heat loss/gain and to prevent condensation on chilled water pipes.

(a) Pumps

Pumps are used to circulate water through the various piping networks associated with building HVAC systems (including chilled water, heating water, and condenser water systems). Pumps are briefly discussed in Section 19.5(b). Centrifugal pumps are commonly used in HVAC systems. Pump performance hinges upon flow rate and head (pressure to be overcome); pump curves allow analysis of pump performance in the context of building performance (including operation at partial loads). Reducing pumping power draw and energy consumption are goals for a high-performance building. Chapter 44 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* provides detailed information on centrifugal pumps.

(b) Piping

Steel pipe and copper tubing are the default materials for HVAC piping systems. Pipe segments will be connected using any of several methods suitable for the pipe type and application. Fittings will be used as required to change direction, transition pipe sizes, and connect to equipment. Pipes will be insulated when heat loss or gain will affect system performance and energy efficiency. ASHRAE Standard 90.1 provides requirements for thermal insulation. Chapter 46 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* provides detailed information on pipes and fittings.

Accessories. Piping system accessories include valves, temperature sensors, pressure sensors, strainers, test ports, and the like. Valves are an integral aspect of water distribution. They may provide manual on-off control for isolating equipment during maintenance, or they may operate under automatic control to meet the control sequences established by the HVAC designer. Chapter 47 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* provides detailed information on valves.

(c) Steam

As discussed in Section 12.6, steam is seeing reduced use as a heat-transfer medium within buildings. Although robust and efficient, steam systems also demand a fair amount of design skill and an infusion of tender, loving care while in operation. Vaporized water is produced by a boiler and distributed to loads via a piping system. At the loads, steam is condensed and the condensate (water) returned to the boiler. Steam traps are installed to ensure that only condensate returns to the boiler. Chapter 11 of the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* waxes eloquent on steam systems.

12.11 AIR DELIVERY

The delivery of air to the various rooms within a building is conceptually simple, but with a fair amount of detail behind the simplicity. Because air is being delivered to another air volume there is no need to interface between different media. Air could in theory just be dumped into a room to heat or cool it. Thermal and acoustical comfort demand greater sophistication. In general, devices termed diffusers, registers, or grilles will be used to introduce supply air into a space and/or allow return air to leave a space. Diffusers are the most refined of these devices; a grille is the least refined. Key design concerns related to air delivery include throw (spatial coverage, for supply devices), airflow capacity, noise production, and aesthetics (which seems to be often overlooked).

(a) Diffusers/Registers/Grilles

A *diffuser* is defined (ASHRAE, 2013) as a circular, square, rectangular, or linear air distribution outlet, generally located in the ceiling, and comprised of deflecting members discharging supply air in various directions and planes and arranged to promote mixing of primary air with secondary room air.

A *register* is defined (ASHRAE, 2013) as a combination grille and damper assembly over an air opening.

A *grille* (ASHRAE, 2013) is a louvered or perforated covering for an opening in an air passage which can be located in a wall, ceiling, or floor.

Supplying air from the ceiling of a space is so widespread a practice that many lighting fixtures are designed to either serve as diffusers for supply air or as intakes for return air. As return air fixtures, they are especially effective because they remove much of the heat from electric lighting before it can contribute a heat gain to the office space below. This reduces the quantity of supply air that must be provided (although the heat from lights must still be handled by the refrigeration system).

With enclosed individual offices, providing a supply diffuser and return grille can ensure good air circulation. As open-plan office space proliferated, so did concerns about whether the workspace cubicles were being adequately served with conditioned air. Air diffusers and grilles (Fig. 12.50) on the ceilings are uncluttered by furniture and independent of rearrangements of workstation cubicles. Canadian research has shown that the most important variable is the quantity of airflow, not the location of the diffusers relative to workstations or whether the cubicle partitions have a small gap where they meet the floor.

Are higher ceilings better for air distribution? There seems to be a trade-off between more vertical clear space (between ceiling and cubicle partitions) that would allow a wider range of air distribution and the increased distance from the actual occupant who should be receiving the conditioned air. An increased distance could allow colder supply

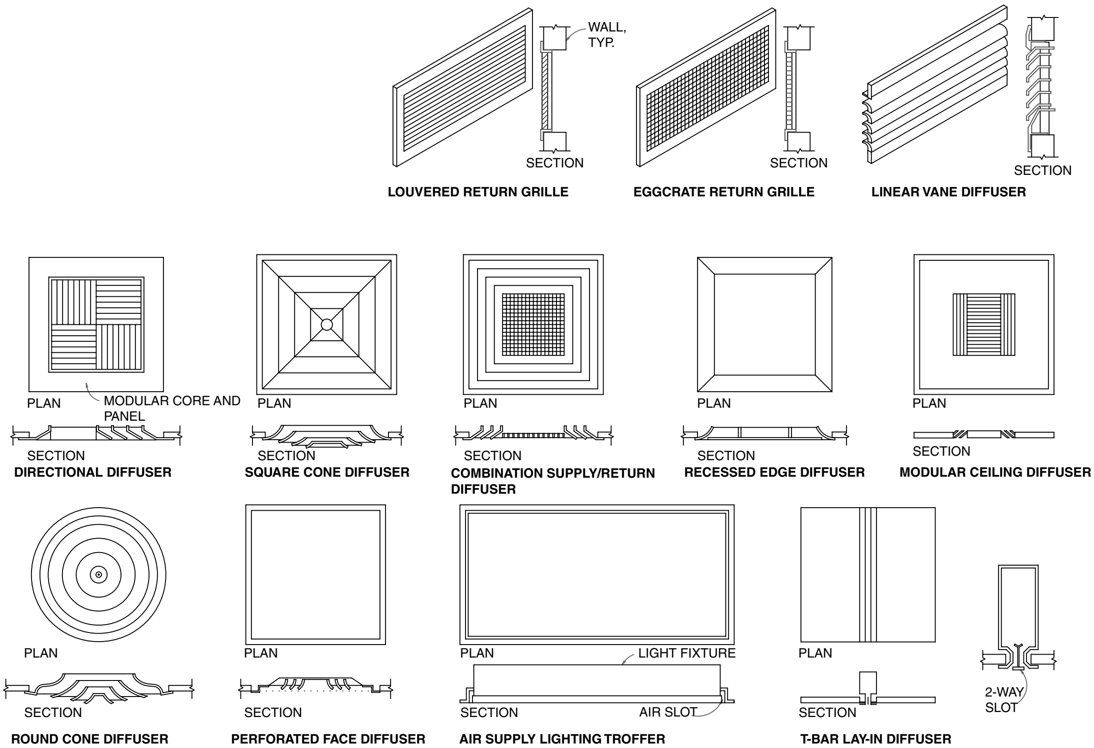


Fig. 12.50 *Common air distribution outlets. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *10th ed.; © 2000 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

air to be distributed, resulting in smaller ducts, and could also allow higher velocity of supply air, further reducing duct size. Higher ceilings allow for deeper daylight penetration and represent a larger "pool" of air that is slower to become polluted by occupants or office equipment.

When noise from diffusers is a critical concern, as in broadcast and recording studios, pinhole-perforated diffusers (Fig. 12.51) can supply large quantities of low-velocity air. These types of spaces pose an especially challenging combination of high heat gains (from lights) and low background noise requirements. Ceiling distribution leaves the floor unencumbered for functional flexibility.

For a discussion of underfloor air supply and distribution, see Section 12.19(b).

(b) Workstation Delivery Systems

The air delivery system shown in Fig. 12.52 allows for a variety of individual control actions at each workstation. The specific system shown, by Johnson Controls, Inc., is called the Personal Environments® system. A mixture of outdoor and recirculated indoor air, termed *primary air*, is brought from the main duct (or floor plenum) to each Personal Environments mixing box via a duct carrying at most 120 cfm (56 L/s), but typically less. Each worker can adjust the supply air temperature, the mixture of primary and locally recirculated air, air velocity and direction, and radiant supplementary heat (below desk level). Task lighting can be dimmed, and the background (masking) sound level is adjustable. A worker has almost as much environmental control at his/her office workstation as a driver has in the front seat of an automobile. When the workstation is unoccupied, an occupancy sensor shuts the system down, maintaining a minimum airflow of 12 cfm (5.7 L/s). There currently appears to be substantial interest in this individualized approach to climate control in Europe (particularly with respect to ventilation).

Fig. 12.51 *Pinhole-perforated diffusers (above a lighting grid) provide large quantities of low-velocity air to the television studio at the Community Media Center of Santa Rosa, California. The background noise from more typical HVAC systems would be picked up by sound recording equipment, which would be unacceptable. (© TLCD Architecture, Santa Rosa, CA.)*

Fig. 12.52 *The Personal Environments® system provides each workstation with a fan, an air filter, an air-mixing box, and a background sound (white noise) generator. The control panel allows adjustment of task lighting, background sound, fan speed, primary/recirculated air mixture, and radiant heating. Two diffusers distribute both air and background sound. Diffusers are adjustable about both horizontal and vertical axes. The below-desk radiant heating panel warms the lower body. (Courtesy of Johnson Controls, Inc., Milwaukee, WI.)*

(c) Alternative Air Delivery Systems

The supply/return systems discussed to this point have focused on the ceiling and the floor. Supply from the ceiling with return through the floor is another possibility when using these two planes for air distribution. Supply air gets to the occupied zone later, and individual control is much more difficult, but floor debris falls into a return, not a supply, plenum.

An alternative delivery approach with return at the perimeter is shown in Fig. 12.53. It is variously called an *air-extract window*, an *air curtain window*, or a *climate window*. Developed in Scandinavia, this is a triple-glazed window that passes room air between a typical outer double-glazed window and an inner single pane. The inner pane thus is kept at very nearly the same temperature as the room air, which greatly increases comfort (via the mean radiant temperature [MRT] effect) near windows on very cold (or very hot) days. Venetian blinds are often inserted in this cavity, where they can intercept direct solar radiation and redirect light toward the ceiling. The solar heat intercepted by the blind is carried off by the room air into a plenum above the ceiling, where the air can be either exhausted or recirculated and its heat content either reclaimed or rejected. The U-factor of these windows is dependent upon the rate of airflow within the glazing panes (Fig. 12.53*c*); typical flow rates are 4 to 6 cfm per foot (6 to 9 L/s per meter) of window width.

The Ocosta Junior/Senior High School at Westport, Washington (Fig. 12.54), uses these windows on the south façade. The classrooms have photocells that switch off some light fixtures nearest the windows when daylight is adequate, and water loop heat pumps help to transfer passive solar

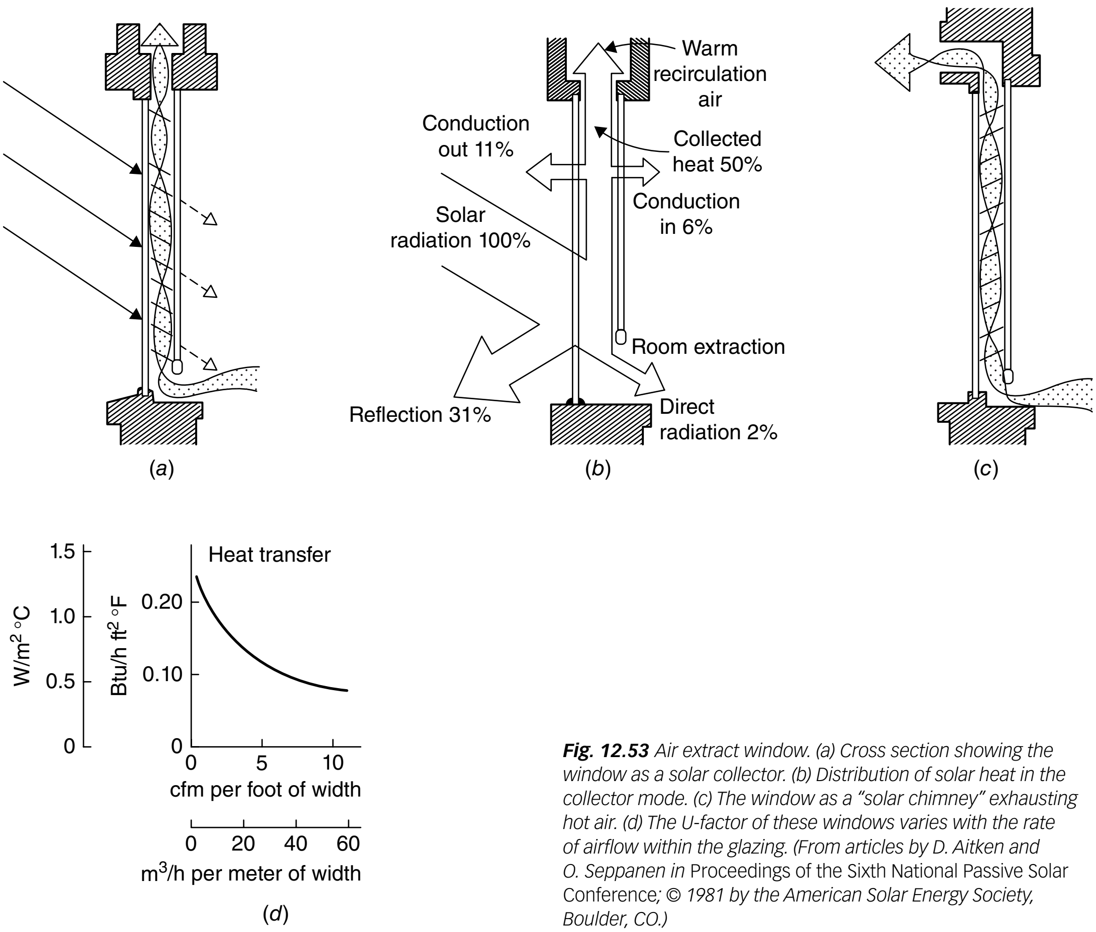
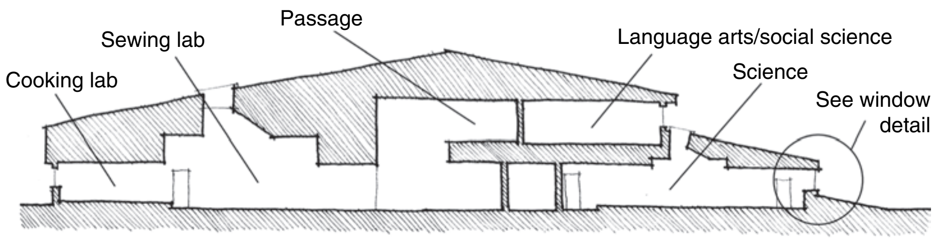
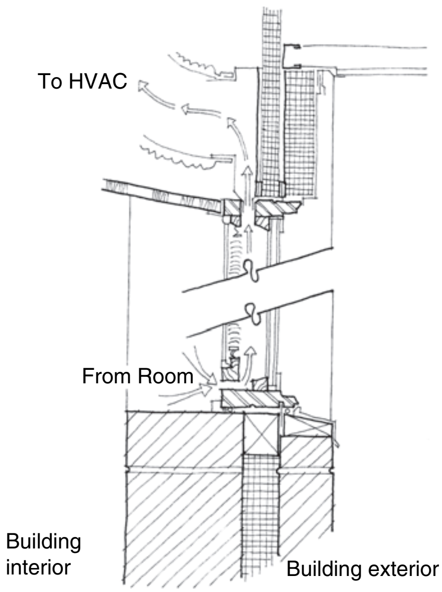


Fig. 12.53 Air extract window. (a) Cross section showing the window as a solar collector. (b) Distribution of solar heat in the collector mode. (c) The window as a "solar chimney" exhausting hot air. (d) The U-factor of these windows varies with the rate of airflow within the glazing. (From articles by D. Aitken and O. Seppanen in Proceedings of the Sixth National Passive Solar Conference*; © 1981 by the American Solar Energy Society, Boulder, CO.)*



(*a*)



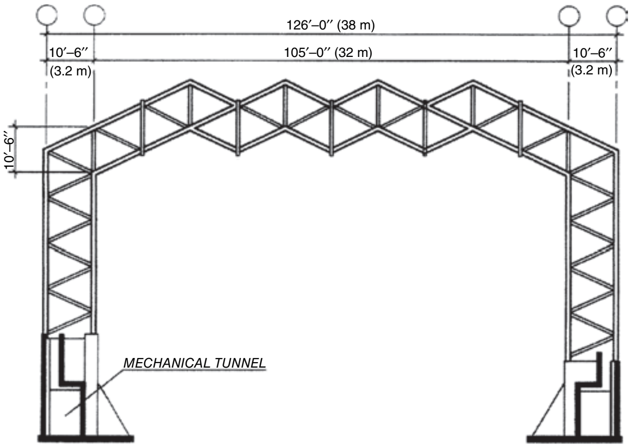
(*b*)

Fig. 12.54 *The Ocosta Junior/Senior High School at Westport, Washington, uses air extract windows to help distribute solar energy from the south side (to the right in section a) to the north classrooms. (b) Detail through the south-facing windows. Photocells control electric lighting during daylight hours; venetian blinds direct sunlight toward the ceiling and deeper into the classroom. (Courtesy of Burr Lawrence Rising + Bates Architects, Tacoma, WA. Redrawn by Erik Winter.)*

heat from the south side to the sunless north-facing rooms. Excess heat is stored in an underground water tank. The compact plan, highly insulated envelope, and thermal mass capacity within the school reduce the need for a boiler to supplement the winter temperature of the water loop. During consistently warm weather, the building management system exhausts the air from the windows to the outdoors. For an example of such windows in a larger U.S. building, see Fig. 12.47, which shows the Comstock Center in Pittsburgh.

Air supply openings in vertical risers are relatively rare but at times function effectively. The Frederick Meijer Gardens (Fig. 12.55) near Grand Rapids, Michigan, is a huge indoor tropical rain forest. This glass structure is more than 65 ft (20 m) high; it has more glass area than floor area—great for a high daylight factor, but imagine the heating loads. High humidity must be maintained, yet water condensation on leaves is undesirable. A strong horizontal airflow could be helpful to the plants, serving as wind would to develop a stronger root structure.

A perimeter tunnel serves as an air supply duct, delivering air evenly around the glass walls, heated by finned tubes located at planting level (which allows them to be largely hidden by foliage). The tunnel insulates the planting beds from the extremes of the exterior, maintaining constant ground temperatures year-round. A separate "wind" system continuously feeds air to vertical ducts with several diffusers (Fig. 12.55*b*), making leaves and branches sway. Humidity is provided by a high-pressure water system that creates fog (very small water particles). This is located high in the space (but also near waterfalls and a stream for



(*a*)

(*b*)

(*c*)

Fig. 12.55 *The Frederick Meijer Conservatory near Grand Rapids maintains a tropical environment in Michigan's winter. (a) A perimeter tunnel delivers air evenly around the walls, heated by finned tubes just above the planting level. (b) A separate "wind" system provides a continuous breeze from diffusers in the vertical ducts to strengthen plant root systems. (c) A fogging system maintains tropical humidity while providing evaporative cooling under summer conditions. (Photos by Roger Van Vleck; courtesy of Fishbeck, Thompson, Carr & Huber, Ada, MI.)*

special effects). This is also an evaporative cooling system to counteract summer overheating. Peak airflow is needed only for cooling; return air is taken through a large opening hidden behind a waterfall. About one-third of the peak supply air is returned; the remainder is exhausted at the top of the structure through operable openings high in the glass roof. A building management system controls the roof vents, the fogging system, the finned-tube heating system, rolling shading screens, and the heating/cooling equipment (located in a basement), all in response to changing conditions surrounding this enormous glass house.

12.12 WATER DELIVERY

Delivering water to spaces conditioned by an air–water or all-water HVAC system is a much more difficult proposition than delivering air. Water cannot be directly introduced to a space. The heating or cooling effect carried by the water must be indirectly coupled to the space through the use of a water-to-air heat exchanger of some sort. Numerous such devices are available to meet the demands of a range of building types and spatial arrangements. A common characteristic of all such devices is their need to consume some amount of room volume (with a few key exceptions—such as recessed convector units or radiant hydronic panels).

The water-to-air heat exchangers that might be used as delivery devices in an HVAC system include:

Hydronic baseboard radiators. These are essentially sections of finned tube with decorative covers; a wide range of capacities and architectural styles are readily available. Air that comes into contact with the finned tube (a mini coil) is heated by indirect contact with hot water, rises by convection, and distributes heat to the space. Air circulation is natural, and no filtering of circulated air occurs. Baseboard radiators are located near the intersection of a wall and the floor, usually on an exterior wall (where heat loss will be concentrated); it is common to see baseboard units located under windows (as a means of offsetting heat loss and increasing glass surface temperature—to improve MRT and resist condensation). Because of their placement near the floor, baseboard units are heating-only devices.

Valence units. These heat exchangers, which have never really caught on, have been used in a few energy-efficient buildings where only a small heating or cooling load exists. The underlying concept is that once freed from being place-bound to heat-loss locations, the intersection between a wall and the ceiling may provide for more flexible use of space. Valence units may be used for heating and/or cooling.

Convectors. Convectors are large assemblages of finned radiation. They can provide a high-output heat source. Flush and recessed cabinet styles are available. natural and forced-convection (with fan) options are possible. Convectors are commonly seen in entry vestibules and similar locations with high heat loss. Located in the lower half of a space, natural convection convectors are typically used for heating; forced convection units might be used for heating and/or cooling.

Unit heaters. This is a heating coil coupled with a fan. The combination of a high-capacity heat exchanger (coil) with high airflow results in a high-capacity device that can be used to heat relatively large spaces. These are commonly used in industrial-type applications.

Hydronic radiant panels. Water tubing embedded in a floor or ceiling can be used as a heat exchanger—and is termed a radiant panel. These panels usually extend the full length and width of a space (although this is not necessary), providing a reasonably low-density heat source that can be very comfortable through its primarily radiant heat exchange. Production installation systems are readily available. Radiant panels may be used for either heating or cooling—although condensation (dew point) control is critical in a cooling application.

Chilled beams. A chilled beam (a misnomer) is a manufactured device that is located at ceiling level to provide radiant cooling to a space; heating is also possible. Passive (without mechanically induced airflow) and active (with mechanically induced airflow) versions are available. Chilled beams are an emerging trend and have generated some controversy as well as buzz in the United States.

Induction units. This is a cabinet (historically installed at floor level) that includes a heating/cooling coil, air filter, and condensate drain pan. Air is provided to the induction unit from a central air-handling unit, along with water from a boiler and/or chiller. The primary air (from AHU) is used to induce a secondary flow of room air across the coil. In North America induction units have been supplanted by fan-coil units.

Fan-coil units. A fan-coil unit is a cabinet with a heating/cooling coil, fan, and air filter. Unlike the induction unit, the fan-coil unit circulates room air by the action of a fan. A wide range of capacities, arrangements, and architectural styles are available (including vertical, horizontal, and stackable configurations).

A designer will need to address the question: Where should water-based delivery devices be placed within a space? The relative comfort provided by radiant ceilings or floors is discussed in Chapter 4. When a smaller delivery device is selected, location becomes more critical. Figure 12.56 shows why designers usually locate heat sources below windows, despite the fact that warmer temperatures just inside an exterior wall will drive more heat through the wall in cold weather (since heat loss = U × A × Δt). As windows and wall assemblies provide better thermal resistance, their interior surface temperatures rise, and the need for heat at the perimeter is reduced. Indeed, with superinsulated envelope components (such as found in Passive House construction), the need for heating virtually disappears because internal gains from the sun, lighting, appliances, and occupants can heat the space.

12.13 AIR FILTERS

Air filters will be found in all-air and air–water HVAC systems. An air filter will typically play two roles in an HVAC system—acting as an indoor air quality mitigation component and protecting HVAC equipment (such as fans and coils) from environmental dirt. When located within a terminal device (such as a fan-coil unit), filter quality and performance are usually aimed at the latter. Chapter 5 provides information on these important HVAC components.

12.14 CONTROLS

Controls and their underlying control logic are a critical part of an HVAC system. Most HVAC systems are actuated and regulated by automatic controls. Most control systems in larger buildings are computerized. The most obvious HVAC control function might be to maintain desired thermal comfort conditions. HVAC controls are just now starting to focus on independently maintaining desired indoor air quality. Controls regularly increase energy efficiency by promoting optimum operation. They act as safety devices, limiting or overriding mechanical and electrical equipment. Automatic controls can also serve to eliminate human forgetfulness and bias. Then again, controls should act in favor of occupant satisfaction.

Although precise control of temperature and humidity everywhere in a building may be a tempting thought, controls can usually maintain only a *range* of conditions, not a specific setpoint. This range is influenced by the accuracy of sensors (cost often is an object) and the deadband of the control

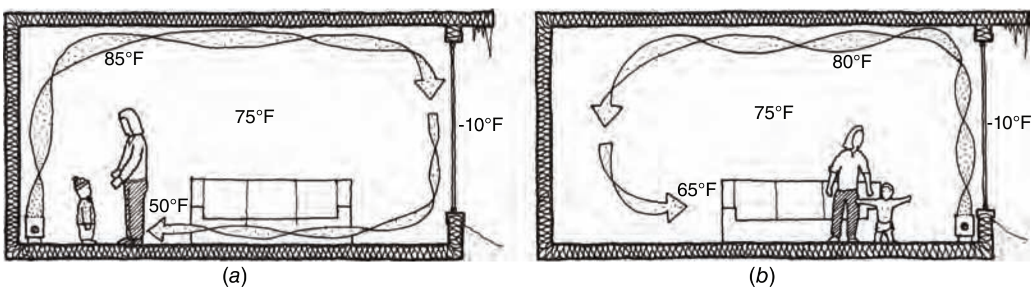


Fig. 12.56 *Locating a heat source near an interior wall (a) encourages a cold draft along the floor in winter. Below a window (b) it evens the temperature throughout the room but also causes more heat loss through the window.*

device (it is not desirable for conditions to change quickly and or in very small increments). In addition, temperature variations will occur vertically within a space—the higher the space, the greater the variation. Variations between horizontal positions within a zone are also highly likely, especially where one or more walls are exterior and where different rooms are combined in a zone. Given all these considerations, in noncritical applications, a control system generally tries to keep a space from becoming uncomfortable.

Individual control components can be classified as follows: *sensors*, which detect conditions; *controllers*, which analyze input data and initiate action; *actuators*, which implement a control action (such as opening a damper or modulating a valve); *limit and safety controls*, which function only infrequently, preventing damage to equipment or buildings; and *accessories*, a miscellaneous collection of special devices.

Control systems can be classified by power source: *electric* (both analog and direct digital control); *pneumatic* (in which compressed air is the motivating force); and *self-contained*, including "passive" controls such as those motivated by thermal expansion of liquids or metals. Control system devices can be classified by the motion of the controller: *two-position* systems are of the simple on–off type; *multiposition* systems have several variations of the on position, and are commonly used for separate operation of more than one machine; *floating* controls can assume any position in the range between minimum and maximum; *central logic control* systems can be programmed to integrate the many aspects of building control into one decision-making unit, and are now the prevalent approach to building management.

Control diagrams for two common HVAC applications are shown in Fig. 12.57. In single-duct VAV systems (Fig. 12.57*a*) with a constantly varying airflow rate, the fan must be regulated so as to maintain the minimum pressure (and therefore, flow) needed at the most demanding outlet. This outlet may be either the one most remote from the fan or the one needing the greatest flow (because it has the highest gain) at the moment. Economizer cycles (Fig. 12.57*b*) compare outdoor conditions to inside conditions, and vary the proportion of fresh (outdoor) air to return air in order to provide "free" cooling (see Fig. 12.124).

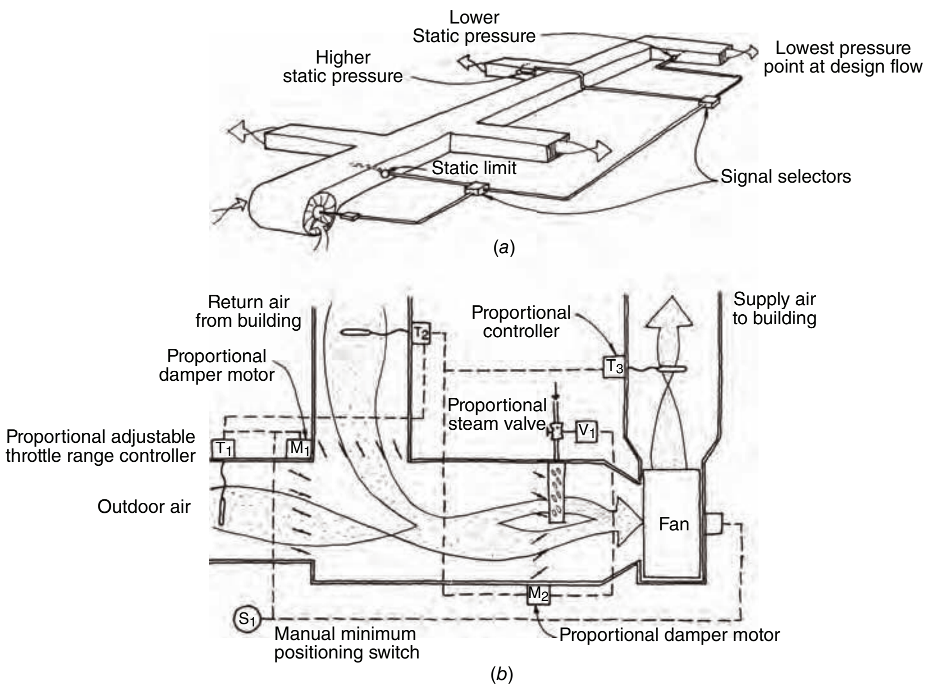


Fig. 12.57 *Controls for some common HVAC applications. (a) Single-duct VAV. (b) Economizer cycle.*

Most of today's large buildings are regulated by centralized control systems, usually called *building management systems* (BMS). The goal of a BMS is a productive, cost-effective environment achieved by optimizing the interrelationships among the building's structure, systems, services, and operation. The HVAC system is centrally regulated and interconnected with lighting, electric power (such as load shedding), elevators, service hot water, access control and security, telecommunications, and information management. Such systems not only maintain comfort with energy efficiency, they also sound the alarm about malfunctions, can learn from past experience, and keep records of system performance.

Aggressive integration and automation of building control systems is made possible through *direct digital control* (DDC), which can be applied to a wide variety of controlled elements. DDC provides "dynamic control" in the case of HVAC, with the ability to anticipate time-based changes in heat flow patterns or in occupancy schedules. These actions depend on direct digital microcontrollers located on each piece of regulated equipment throughout the building. Three building types show applications of this comprehensive automated control opportunity.

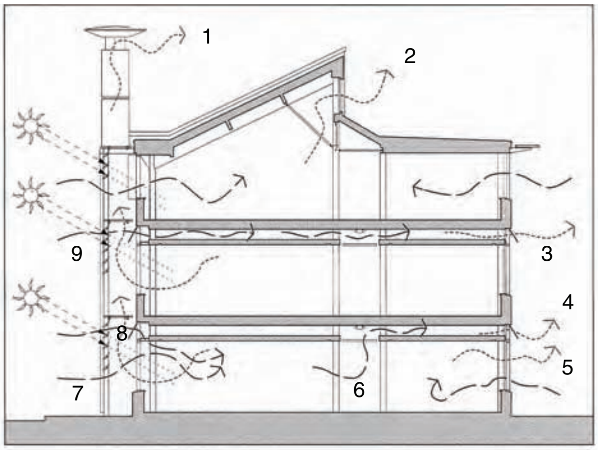
Laboratories tend to present especially difficult HVAC control problems due to their many fume hoods. Conditioned air is provided from a central HVAC system, often by a VAV supply. Whenever a fume hood is exhausting air (frequently in huge quantities), the VAV supply and return systems are affected. Complicating this relationship is the nature of the laboratory work; when an experiment could be damaged by outside contaminants, the lab should be positively pressurized to minimize infiltration (and the VAV must therefore provide a net air flow of slightly *more* air than the fume hood exhausts). However, when experiments involve diseased, toxic, or other hazardous substances, the lab must be negatively pressurized (and the VAV must supply a net of slightly *less* air than the fume hood exhausts). DDCs tied to a central system can balance energy efficiency, lab worker safety, and safety for the nonlab environment.

Hotel rooms can present serious energy waste problems from heating/cooling an unoccupied room or a room with open windows. With DDCs interconnected with the registration desk, an "unoccupied" mode of operation can be remotely established, with bare-minimum heating or cooling. When the room is occupied, the heating/cooling supply can be throttled back whenever a window is open. Also, a "purge" mode can enable a new arrival (or the front desk, in anticipation) to select a greatly increased flow of outdoor air for a limited time period to dilute odors. Chapter 31 presents more detailed information on *intelligent buildings*—for which some of these control ideas are precursors.

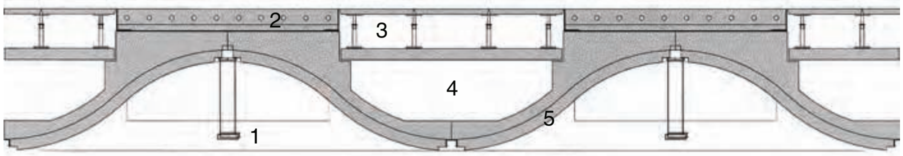
Offices might be provided not only with DDC for the VAV supply units, but also with DDCs for an interconnected network involving a ventilating window (preventing simultaneous open windows and HVAC delivery), daylight reflectors (mini-lightshelves), venetian blinds, a radiant heater valve, an electric light switch, and an insulating shade. A control panel or "dashboard" can give each worker the opportunity to interact with the central control in operating these devices.

Office buildings that use passive strategies can also benefit from a BMS. The British Research Establishment building for fire research, "Building 16" (Fig. 12.58), depends upon cross ventilation and stack ventilation for its cooling, and upon movable louvers on the south windows for sunshading and daylight distribution. A common network links this building's control systems; each worker has a TV-like controller that regulates lighting and can override the programmed settings of the nearest high-level windows (for ventilation) and south-window louvers (for sun control and daylighting). This innovative office building uses a ground-source heat pump (vertical type) to supplement solar and internal winter heat gains or to provide supplementary cooling to the night ventilation system. Note the provisions for cross-ventilation for individually enclosed offices on the ground floor, utilizing a cavity above the ceiling to carry ventilation air to an exhaust on the other side of the building.

Rapid changes in centralized control systems continue to occur. Initially, DDC systems were developed by individual companies, with little or no opportunity for communication between systems. Such proprietary systems left designers frustrated by an inability to specify a wide variety of products that could all be controlled by a single BMS. In the late 1990s, two competing systems had emerged that promised integration of products and systems from different manufacturers. BACnet



(a)



(b)

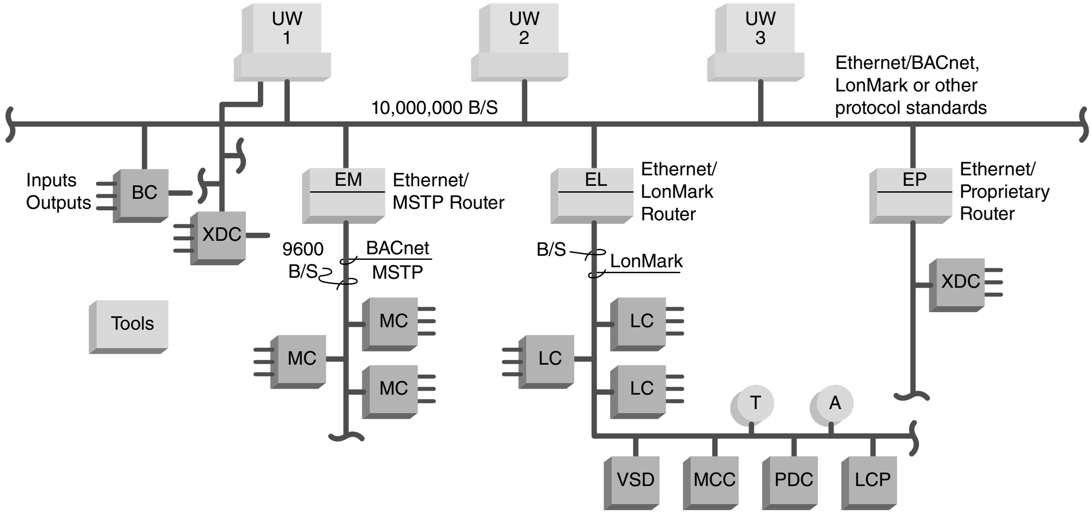
Fig. 12.58 *Natural ventilation and daylight strategies dominate the north–south section (a) of the British Research Establishment Building 16. (1) Stack ventilation (hot, calm); (2) clerestory BMS-controlled ventilation; (3) night ventilation through slab, BMS-controlled; (4) cross-ventilation bypass over enclosed offices; (5) enclosed office single-sided ventilation; (6) corridor cross-over zone; (7) manually operated lower-level windows; (8) high-level BMS-controlled windows; (9) motorized external shading louvers, also BMS-controlled. (b) East–west section detail of precast floor structure. (1) Luminaire with integral photosensors; (2) heated/cooled screed using a ground-source; (3) raised access floor for wiring; (4) cross-ventilation duct (night ventilation and/or cross-over ventilation for enclosed offices); (5) waveform precast concrete ceiling with poured-in-place topping slab. (Courtesy of Feilden Clegg Architects, Bath, England.)*

was developed by ASHRAE as a nonproprietary communication standard. LonMark was developed by the LonMark Interoperability Association, a user-funded organization of building owners, specifiers, system integrators, and product suppliers. *Open control system architecture* is an approach that is intended to let components from several vendors interoperate over a BACnet-adapted Ethernet LAN (local area network). It makes possible a system combining BACnet, LonMark, and proprietary subsystems (Fig. 12.59).

Wireless control systems appear to be an emerging trend. A wireless system has both plusses and minuses. A big plus is the lack of need for power and data wiring at a hundred or multiple hundreds of locations in a building. This can reduce the cost of control systems and make retrofit installations feasible. Minuses include the need to change batteries on hundreds of devices scattered around a building in often inaccessible locations, and problems with wireless signal reception in some buildings. It is likely that the plusses will eventually outweigh the minuses, and wireless control systems will become more common.

Other, more esoteric, control possibilities (such as self-diagnosing equipment monitors, nanocontrols, and neural networks) lie on the horizon. *Neural networks* involve automation systems that are capable of learning from use. They can predict usage patterns, adjusting operations in advance without needing specific commands from occupants. When the building use pattern is highly predictable, as with many retail and commercial occupancies, these self-programming systems can learn very quickly how to anticipate needs while conserving energy.

Open Building Management and Control System



A	- Intelligent actuator	MCC	- LonMark-compatible motor control center
BN	- BACnet native controller that connects directly on the Ethernet/BACnet bus	MSTP	- Master/Servant Token Passing protocol
EL	- Ethernet/BACnet-to-LonMark router	UW	- User workstation with BMCS and BACnet software and Ethernet card
EM	- Ethernet/BACnet-to-BACnet Master/Servant Token Passing (MSTP) protocol router	PDC	- LonMark-compatible power distribution center
EP	- Ethernet/BACnet to a proprietary protocol router	T	- Intelligent temperature sensor
LC	- LonMark-compatible controller	Tools	- Programming, maintenance, and diagnostic tools required
LCP	- LonMark-compatible lighting control panel	VSD	- LonMark-compatible variable speed drive
MC	- BACnet/MSTP compatable controller	XDC	- Proprietary digital controller

Fig. 12.59 *Building management system (BMS) that is open to various protocol standards. (Courtesy of Honeywell, Inc.)*

Residences are seeing increasing use of remote control and automation (in many cases promoted by utilities or cable companies). Residential building management systems are now capable of regulating far more than temperature. They can activate systems in advance of the occupants' arrival and provide real-time status reports on building conditions. Door and window locks, security cameras, lighting, and appliances are potential actors in a comprehensive control system.

In residences, usage patterns are varied and difficult to predict. Experiments at the University of Colorado revealed that, even so, patterns may be more predictable than was first thought (Mozer, 1998). The Adaptive Control of Home Environments (ACHE) system has two objectives: to anticipate occupants' needs and to save energy. Lighting, air temperature, ventilation, and water heating are controlled so that just enough energy, just when needed, is provided. Lighting would be set to the minimum required levels, hot water maintained at the minimum temperature that would meet demands, only occupied rooms would be kept at a comfortable temperature, and so on.

The control framework then compares energy costs to "misery" costs. Minimum settings and their time patterns are developed as the building is occupied over time. Whenever a preset minimum is overruled by an occupant, the system learns and readjusts accordingly; however, it occasionally tests lower settings to be sure that energy conservation is not being unduly sacrificed to ingrained past practices.

HVAC SYSTEMS

With an understanding of fundamentals and components in place, it is reasonable to look at examples of actual HVAC systems and their application in buildings. Considering the wide variety in possible design objectives and the large number of individual components that may be assembled into an HVAC system, it should be clear that not every possible system will be addressed in the coming pages. It is also good to remember that all but local HVAC systems are field-assembled from a large number of components that are provided by a variety of suppliers and manufacturers. For example, the HVAC system in a single-family residence may use a heat pump from manufacturer "A," ductwork from fabricator "B," piping from hardware store "C," an energy recovery ventilator from manufacturer "D," and so on. Most HVAC systems are truly unique—often resembling other systems, but never quite replicating them. A lot of things can go wrong in such a scenario, so the commissioning process is highly recommended.

12.15 HVAC SYSTEMS TAXONOMY

(a) System Scales

Starting from the philosophy that a sense of taxonomy can help with the understanding of complex systems, a classification of HVAC systems is presented. HVAC systems are commonly classified by scale as:

- Local: A local system is usually intended to serve one zone (with the zone usually consisting of one or at most a few rooms). The system is self-contained (the source, distribution, delivery, and control components are close-coupled and generally within one package). The system is usually located within the space being served (with implications for aesthetics and flexibility). The system is typically of small capacity and small size (with impacts on efficiency). The system is not commonly controlled from a centralized location (this can be a positive or a negative consideration). A window air-conditioning unit is an example of a local HVAC system.
- Central: A central system serves multiple zones from one location (or one zone from a remote location). A distribution system is required to transport heating/cooling effect from its place of origin (such as a mechanical room) to the system zones. System scope can vary greatly, from a single-family residence to thousands of square feet (square meters) of office or laboratory. A building may be served by one central system or by multiple central systems. A variable air volume (VAV) system is an example of a central system.
- District: A district system serves multiple buildings. Normally district systems provide heating and/or cooling effect for campuses or special utility zones. The buildings being served usually have their own central HVAC systems. Economies of scale are possible with the large-capacity equipment typical of a district system (this can include bulk purchase of fuels or electricity, customized operating control sequences, outstanding maintenance quality, and highly trained operators). Ball State University's new ground-source heat pump system (Ball State University, 2013) is an innovative example of a district system.

Long-distance steam distribution has been used for more than a century; the development of *high-temperature water* (HTW) and chilled water distribution among buildings is a more recent development. Offering many advantages, high-temperature, high-pressure hot water and chilled water systems are widely used on U.S. Air Force bases, airports, and for groups of buildings such as hospital complexes and college campuses. Increasing efforts are being made to install new district heating/cooling networks served by existing fossil-fueled electricity generating plants. Such plants waste more than half of their fossil fuel input, and district heating/cooling could utilize much of that waste.

Water will not flash into steam if kept at sufficiently high pressure. It may then be circulated by pumps through supply and return mains and through branches to heat exchangers, which operate conventional low-pressure hot water systems, generate steam, and perform numerous other thermal tasks. Pressures are on the order of 400 psig (pounds per square inch, gauge; [2800 kPa]) and temperatures are about 300°F (150°C). During its circuit, the water will sometimes lose up to 150F° (83C°) and 60 psig (414 kPa) in pressure. The section shown in Fig. 12.60 illustrates a common arrangement.

High-temperature water has a number of advantages over steam for certain installations. It uses a two-pipe distribution system, and the temperature drop in the supply main is often as little as 10F° (5.5C°). With reasonably high water

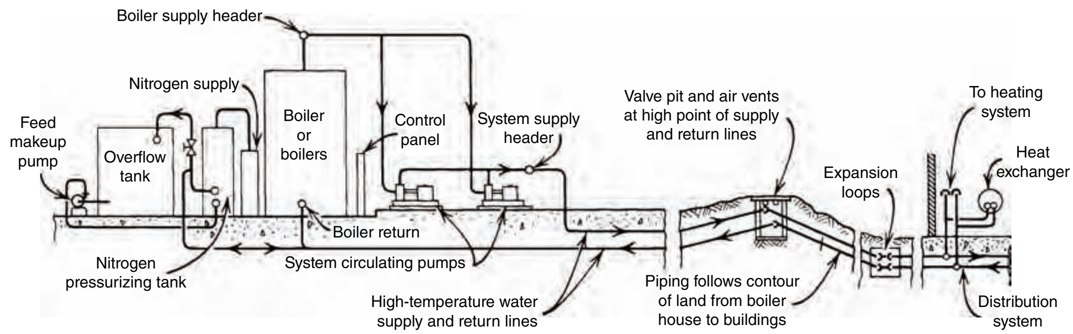


Fig. 12.60 *Typical arrangement of a high-temperature water system. (Reprinted from* High-Temperature Water Systems*. Industrial Press. By courtesy of author Owen S. Lieberg, consulting engineer.)*

velocities, main pipes can be reduced to almost half the size of those required for steam distribution, with no need for steam traps and pressure-reducing valves. The pipes need not pitch to low points (to accommodate condensation), as is the case with steam, but can follow the contours of the ground. Although installation costs are greater, operational costs are less than those for steam. Feed water treatment is negligible and corrosion is minimal. Expansion and insulation issues are the same as in other subterranean systems. Large sweep-type loops accommodate expansion between fixed points, and underground piping is embedded in thermally effective insulative fill.

District chilled water systems also offer advantages. Large central chillers are likely candidates to use waste heat in a non-CFC absorption refrigeration cycle. Natural coolth sources are possible; the Toronto (Canada) District Heating Corporation uses Lake Ontario water, drawn from a 1.6-mile (2.6-km) intake at a depth of 200 ft (61 m) with a year-round temperature of 40°F (4.5°C). Passed through a heat exchanger (with the district chilled water) and then treated, the lake water then joins the city water supply.

With district heating/cooling, all source components are located together in a remote district plant. This frees other buildings from the space requirements and visible impacts of stacks, boilers, fuel storage, water chillers, and cooling towers; the associated heat, humidity, fouled air, and noise are as remote as the district plant. When such a system serves commercial customers, the heated or chilled water is metered. When it is self-owned (such as on a college campus), it is usually not metered; this can become a problem when efforts to identify building energy waste and subsequent savings are undertaken.

(b) Distribution Media

Distribution of heating/cooling effect is (with the exception of steam) accomplished using either water or air—or water and air. There are thus three distinct classifications of central HVAC systems:

- *All-air*: In an all-air system, the heating/cooling effect is distributed from the source(s) to the spaces via heated or cooled air transported in ductwork; water is not used to transfer heat to/from the conditioned zones. The primary benefit of an all-air system is that air is used to modify the condition of air (sounds circular, but this approach is direct and logical); the main issue to be confronted in some building projects is the spatial volume that must be allocated to the ductwork. Conditioned air is delivered to the various spaces through diffusers/registers. An all-air HVAC system (of some configuration) should be able to readily meet the owner's project requirements for thermal comfort, IAQ, and energy efficiency.
- *Air–water*: In an air–water system, the bulk of the heating/cooling effect is distributed from the source(s) to the spaces via hot or cold water transported in pipes. Air is also supplied to the spaces from a centralized unit—typically only enough air to ensure desired indoor air quality;

this is often roughly 10% of the airflow seen in an all-air system. This air can also transport some heat/coolth. The primary benefit of an air–water system is reduced demand for distribution volume (piping is smaller than ductwork for equal heat transport). A concern in some building projects is the placement of water-to-air heat exchangers (the delivery devices) within the occupied spaces. An air–water HVAC system (of some configuration) should be able to readily meet the owner's project requirements for thermal comfort, IAQ, and energy efficiency.

- *All-water*: The heating/cooling effect is distributed from the source(s) to the spaces via heated or cooled water transported via piping and introduced to the spaces via heat exchange delivery devices. Air is not used to transfer heat to/from the conditioned zones and is not supplied to the spaces by the HVAC system (air may be introduced to the spaces independently, for example by passive means). The primary benefit of an all-water system is that the spatial volume required for distribution will be the minimum possible (ducts are not used at all); a critical issue to be confronted when considering an all-water HVAC system is its ability to meet the owner's project requirements for IAQ.

12.16 HVAC SYSTEMS ANATOMY

(a) Building Scales

Larger buildings are generally more complex than smaller buildings. This also holds true for HVAC systems. This discussion of system anatomy will begin with smaller-scale building considerations (buildings with, say, one to five thermal zones); larger-scale building situations will then follow.

Smaller buildings are typically skin-load (or envelope) dominated; the climate (rather than internal loads) dictates whether heating or cooling is the major design concern. In some climates, only heating is needed; a building can "keep itself cool" during hot weather without mechanical assistance. In other climates, only cooling is needed. In still other climates, both heating and cooling are required. It should be noted that "required" is in the eye of the client as well as in the climatic record—expectations for systems can drive decision making as much as design analysis.

A skin-load-dominated building may have such differing but simultaneous needs that a room-by-room solution for heating, ventilating, and cooling is desirable. Such a situation would suggest adoption of a *local* HVAC system approach. Consider the building with both north- and south-facing spaces on a cold, sunny winter day; one side gets ample solar heat, while the other side needs additional heat. An advantage of local systems is their ability to respond quickly to individual room (zone) needs.

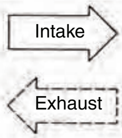
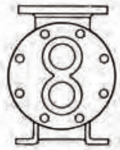
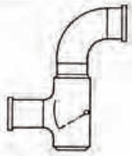
A *central* HVAC system also has advantages: The equipment is contained within its own space rather than taking up space within each room, and maintenance can be carried out without disrupting activities within the occupied rooms.

Section 12.4(f) discussed equipment space requirements for large buildings. Determining the approximate size of small-building HVAC equipment during schematic design is also useful. Once design heating and/or cooling loads are known, manufacturers' catalogs can be consulted for the dimensions of appropriate heating and cooling equipment. A critical decision in sizing HVAC equipment regards the *design temperatures*: What are reasonable outdoor and indoor temperatures that would inform the selection of the system—and how to consider climate change?

The preliminary determination of required cooling capacity is not so straightforward. A *very approximate* early estimate can be obtained, however, from the estimated hourly gains listed in Table G.3. This type of estimate is likely to be *lower* than that obtained using the peak heat gain hour, for which cooling equipment is often sized. The ton is a commonly encountered unit of cooling capacity. One ton is the equivalent useful cooling effect of a ton of ice; this is 12,000 Btu/h (3516 W).

Larger buildings are typically internal-load dominated; lighting, people, and equipment/appliances tend to dictate the overall mix between heating and cooling requirements. Interior areas of a building often have no thermal connection to the outdoor environment; all loads are internal. All buildings, however, will have perimeter areas which interface with the outdoor environment through the building envelope. A design challenge is to ensure that an HVAC system can respond to such varying needs—both across space and across time.

TABLE 12.4 Basic HVAC System Tasks and Components

 Intake Exhaust	 Production/Motion Movers, converters, processors	 Distribution Supply and return trees, delivery and control components	 Results
Heat: Fuel Combustion Air Heat CO_2	Boilers Furnaces Pumps Fans Filters Heat pumps	Pipes Ducts Electricity conduits Diffusers Grilles Radiators Thermostats Valves, dampers	Warm air or surfaces Air motion often controlled Humidity control sometimes needed
Cool: Air Water Fuel Air Vapor Water Heat CO_2	Evaporative coolers Heat pumps Chillers and cooling towers Coils Pumps Fans Filters	Pipes Ducts Diffusers Grilles Radiators Thermostats Valves Dampers	Cool air or surfaces Air motion usually controlled Humidity control usually provided
Vent: Air Air	Fans Filters	Ducts Diffusers Grilles Switches Dampers	Fresh air Air motion usually controlled Air quality control often needed

Source: Class notes developed by G. Z. Brown, University of Oregon.

The following discussion is aimed primarily at such larger buildings.

Table 12.4 describes the basic parts of any HVAC system—and reinforces the concepts of source, distribution, delivery (and controls). Three common tasks (heating, cooling, and ventilating) are accomplished. Intakes and exhausts accompany each task. Although the final choice of HVAC system should follow a detailed analysis of the owner's project requirements, some basic concepts (introduced previously, and expanded herein) will underlie system choices.

Central systems require one or several large mechanical spaces (often located in a basement and/or on a roof), sizable distribution trees, and sophisticated control systems. The noise, heat, and other environmental conditions of such mechanical rooms can be controlled fairly easily, because the conditions are concentrated in a few locations not occupied on a regular basis. Similarly, maintenance is easy to perform without interrupting normal activities, although breakdowns in central equipment can paralyze an entire building. Air quality can be improved by locating air intakes high above street level pollution and by regular maintenance of centralized air filters. Longer equipment life can be expected with regular maintenance. Energy efficiency can be served by the recovery of waste heat by-products. Also, there are many ways to provide for the differing thermal needs of the many zones that will be served by a central system. One important drawback of a central system is the potential size and length of the distribution tree(s) required to carry centralized services to many distributed spaces. Another potential drawback is scheduling of operations caused by differences in zone usage. Energy may be wasted when an entire HVAC system must be activated to serve one zone (such as a computer server space) when all other zones can be dormant.

Local systems may be attractive even for large buildings as scheduling differences between zones multiply. Also, pronounced differences in other factors—for example, function (with resulting comfort expectations) or placement within a building—can lead to the selection of a local system (usually, multiple local systems). Large centralized equipment spaces are not required with local systems; rather, source equipment is distributed throughout a building (or over the roof and/or surrounding grounds). Dispersal of equipment minimizes the size of distribution trees (or eliminates them altogether) and greatly simplifies control systems. Moreover, a system breakdown will affect only a small portion of a building. Noise and other effects of local equipment, however, can cause discomfort in occupied spaces, and make quality maintenance challenging (because access to so many separate locations may be disruptive or restricted). Good air quality depends upon the regular cleaning of air filters, which is more difficult when they are scattered around a building, and are often within occupied spaces. The potential for energy conservation with local systems is promising, mainly because system operation and control are local and personal, but there is little opportunity to capture waste heat as a resource.

A central system approach does not imply that all spaces must be served from a single location. Several central locations/systems may be used within a building. This is shown in Fig. 12.61*b*, where a central boiler/chiller space is remotely located, and fan rooms are located on each floor. This greatly reduces the size of the bulky air distribution tree; although the distribution tree for hot and chilled water is extensive, the pipes are of much smaller diameter and therefore relatively easily accommodated and coordinated. The use of a central equipment room makes energy recovery systems more feasible.

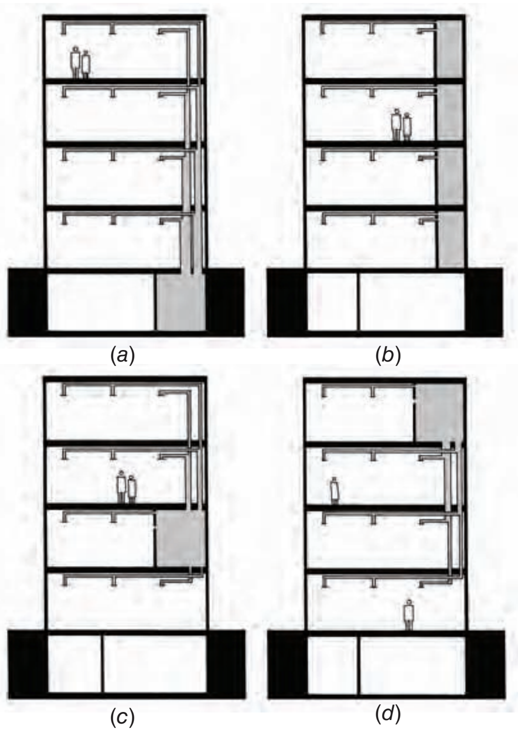


Fig. 12.61 *Fan rooms (gray spaces) can either be combined with or separated from boiler/chiller "plant" rooms. (a) Common location for a central combined equipment room. (b) Increasingly common arrangement of a small fan room on each floor, with a plant room in the basement. (c) An intermediate floor may be able to provide space for a central fan room, while heavier and noisier equipment remains in the basement. (d) With a top-floor central fan room, plant equipment may be located either on the roof or in a mechanical penthouse, or it may remain in the basement. (Adapted by permission from E. Allen and J. Iano,* The Architect's Studio Companion*, 5th edition; © 2012, John Wiley & Sons, Inc.)*

(b) Zones and Systems

When selecting systems from among the wide variety available, it is helpful to match zone characteristics and system characteristics. Among the considerations are zone placement (close to or away from the building skin), zone thermal loads, the comfort expectations related to the zone activities, the space available for system components within the zone, and the life-cycle costs of various system alternatives.

Zone placement will sometimes preclude local systems, which depend on easy access to outdoor air both for fresh air and for a heat source or sink. Local systems for interior (away-from-skin) zones can be awkward. Relationships between zone placement and building forms are shown in Fig. 12.62.

The thermal loads on each zone determine the extent to which heating or cooling is the dominant problem—which, in turn, can influence the

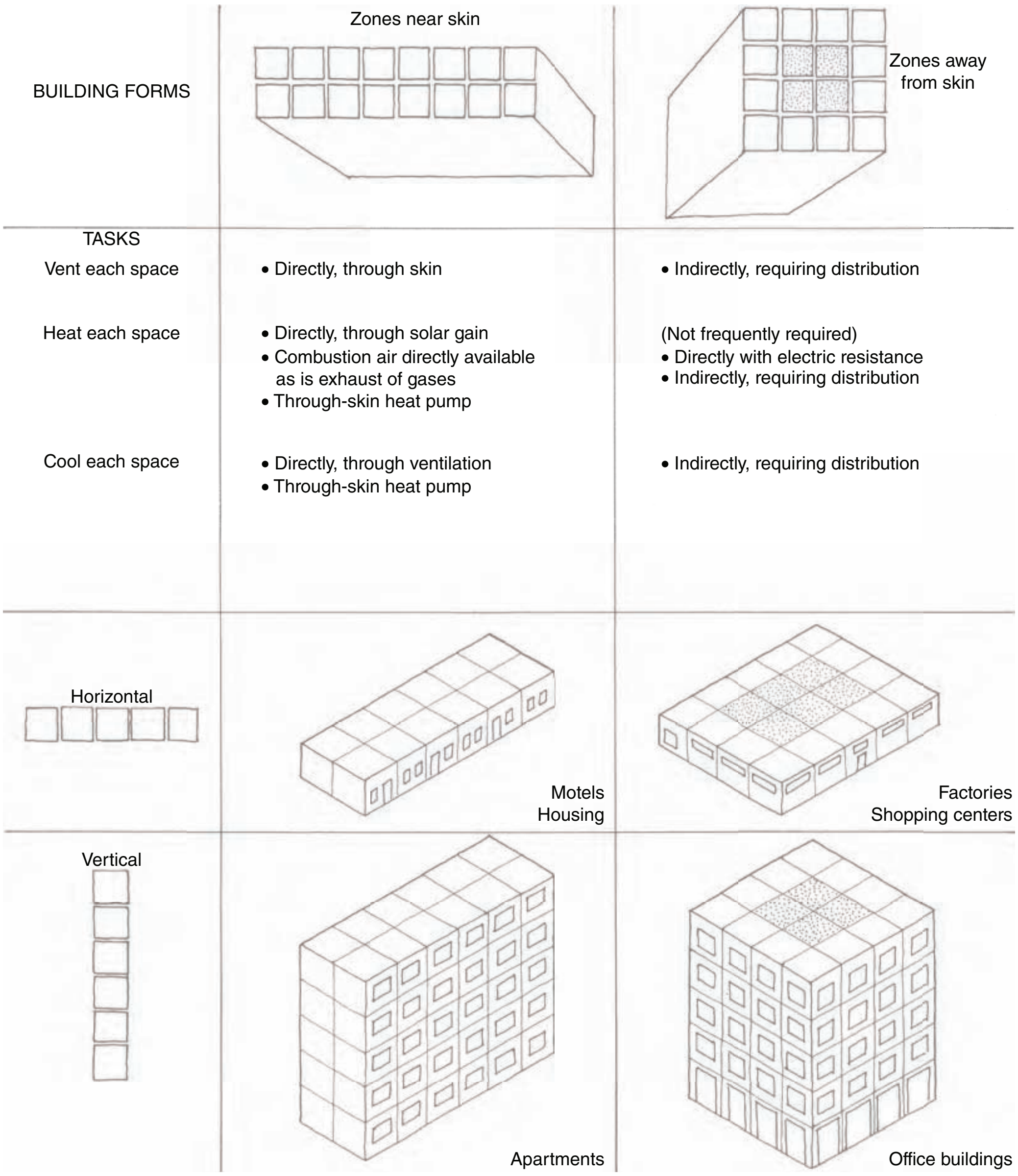


Fig. 12.62 *Zone placement and building form are related to heating, cooling, and ventilating tasks; some applications take on typical building forms. (From class notes developed by G. Z. Brown, University of Oregon.)*

TABLE 12.5 Linking Thermal Comfort and Thermal Control

	For Heating of Spaces	For Cooling of Spaces
More important	Surface, air temperatures	Air motion
↓	Air motion	Relative humidity
Less important	Relative humidity	Air, surface temperatures

choice of system. A zone with little cooling load and low moisture production may be well served by a simple system providing fresh air plus heating, with no humidity control. Zones that require cooling will usually also require more complete control of air motion and relative humidity. Although it is risky to generalize about which comfort determinants are most important (given the differences between activities and between individuals), it can generally be assumed that comfort and thermal tasks are related. This relationship is summarized in Table 12.5. The choice of system may be based partly on whether a system can provide appropriate control of the more important comfort determinants.

Distribution Trees

Central heating/cooling systems produce a heating and cooling effect in one place, then distribute the effect to building spaces according to their respective needs. A tree is a metaphor for the means for distributing heating and cooling: The "roots" are the source machines that produce heat and cooth, the "trunk" is the main duct or pipe from the source equipment, and the "branches" are the many smaller ducts or pipes that lead to zones and individual spaces.

Questions regarding distribution trees might include: How many? What kind? Where? A building can have one giant distribution tree, several medium-sized trees, or a veritable orchard of much smaller trees. At one extreme, a large mechanical room is the scene of all heating and cooling production; leading from this room is a very large trunk duct with perhaps hundreds of branches. At the other extreme, each zone has its own mechanical equipment (such as a rooftop heat pump), with short trunks and relatively few branches on each tree.

What kind of distribution tree? Basically, the options are air (ductwork) or water (piping). Air distribution trees are bulky and therefore likely to have major visual impacts unless they are concealed above ceilings, below floors, or within vertical chases. Water distribution trees consume much less space (a given volume of water carries vastly more heat than does the same volume of air at the same temperature) and can be easily integrated within structural members such as columns. Air and water trees can both be noise sources.

How does the distribution tree relate to the building? If placed on the exterior, it can lend a three-dimensional organizational structure to a façade. Exterior distribution trees consume less enclosed and conditioned floor space but require expensive cladding and are subject to considerable heat losses and gains, which could increase energy usage. Interior trees are often housed in shafts and grouped with other continuous vertical spaces, such as elevator shafts and stairways. If the choice is an exterior distribution tree, its potential contribution to façade performance should be considered and architecturally integrated. For example, ductwork might act as a sunshade or as a light shelf or as a visual organizing element.

HVAC system choice will be influenced by the amount of space the system requires. In some cases, it is easy to provide small equipment rooms at regular intervals throughout a building, such that little or nothing in the way of a distribution tree will be required. In other cases, a network of distribution trees and large central equipment spaces may be easier to accommodate. Figure 12.63 shows a matrix relating the influences on distribution trees of centralized/dispersed versus air/water systems.

To carry the tree analogy to its logical conclusion, consider the "leaves" as the delivery elements: the points of interchange between the distribution network and the spaces being served. Delivery device selection can substantially affect the aesthetics and usability of a space. Consider a bulky device such as a fan-coil unit on an exterior wall below a window versus a perforated ceiling diffuser that may be essentially invisible.

The issue of distribution trees relates to the selection of an HVAC system and its ability to provide appropriate zoning. A simplified procedure

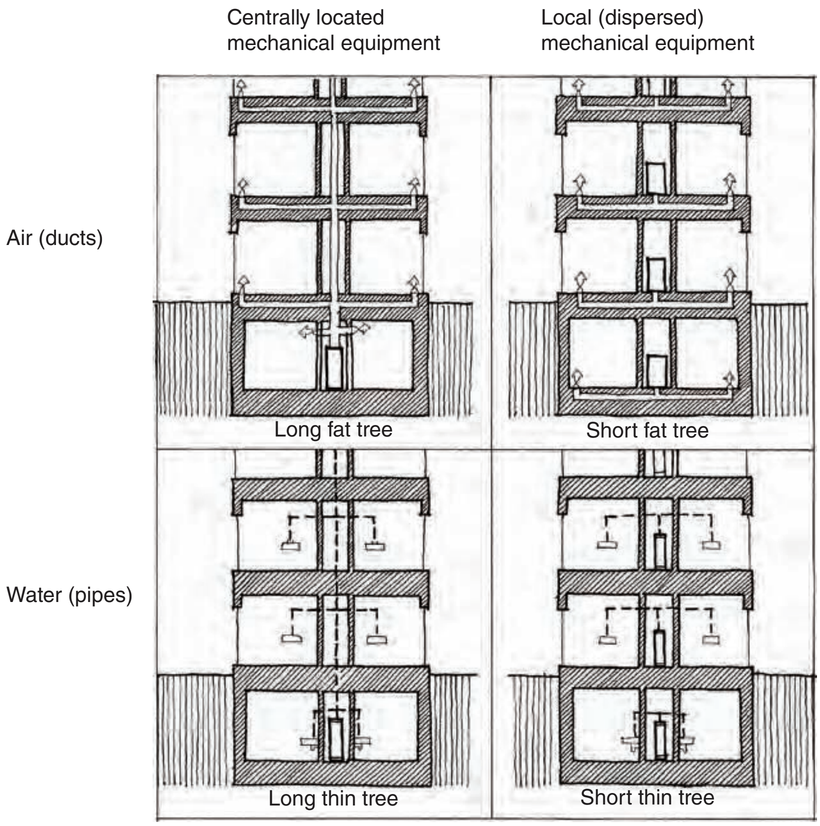


Fig. 12.63 *Matrix of distribution trees. (© 1998 John S. Reynolds; drawing by Michael Cockram.)*

for matching zone requirements and system capabilities is shown in Table 12.6, in which preliminary system choices are made for a building such as the multipurpose structure suggested in Fig. 12.5. Using this process, the basic 16 zones are translated into three local systems and three central systems: one all-air, one air–water, and one all-water.

The Fox Plaza Building in San Francisco, which illustrates many such matches between systems and zones and resulting distribution trees, is shown in Fig. 12.64. This project includes four major building types in one structure:

1. Underground parking garage
2. Commercial center at ground level, including a bank, a women's specialty store, and other commercial establishments
3. Ten floors of offices
4. Sixteen floors of apartments

The mechanical room/level is located between the office portion of the building and the apartments above. The distribution trees—HVAC, electrical, and so on—are thus directed both upward and downward, resulting in two shorter trees rather than one longer tree. The spatial requirements of offices and those of apartments are quite different; thus, the floor-to-floor heights, window treatment, and HVAC, electrical, elevators, and other services are different. The placement of the mechanical level between the offices and the apartments also provides for a definite visual separation between the two functions.

Quite unusual is the placement of the steam boilers on the 13th floor instead of in a more conventional basement location. Only a small amount of auxiliary equipment is located on the roof and in a small portion of the garage. Residential areas have hot-water heating (residential cooling being

TABLE 12.6 Procedure for Matching Zones and Systems

CAPSULE DESCRIPTION

A multipurpose building is situated in a cold winter/mild summer climate.
Apartments are on upper floors surrounding an open-air central court; they have adequate daylight and cross-ventilation. Floor-to-floor heights are low.
Offices are rented to various tenants. Exterior offices have high ceilings to facilitate daylighting, low internal gains, and restricted clearance for horizontal ductwork. Interior offices have lower ceilings; vertical chase space is limited because it reduces rentable area.
Shops are located around the perimeter on the high-ceilinged ground floor; some smaller shops are located on the mezzanine and ground floors in the interior zone. Space for vertical chases is severely limited on these highly rentable floors.
The parking area is belowground, surrounded by air/light wells. Floor heights are very limited to reduce ramp length.

Activities (Program)	**Apartments**	**Computer Center**	***Offices***		***Shops***		**Restaurant**	**Parking**
Schedule	24 hours	24 hours	9 hours		9 hours		12 hours	
Placement	Exterior	Exterior for access	Exterior	Interior	Interior	Exterior	Exterior for access	Entire floor
Internal gains	Vary	High	Low	Medium	High	Medium	High plus moisture	Low with exhaust gas
Dominant HVAC task(s)	Heat-ventilate	Cool	Heat/cool	Cool	Cool	Cool	Cool	Ventilate
HVAC space available								
Vert. (in plan)	Medium	Medium	Medium	Tight	Tight	Tight	Tight	Medium
Horiz. (in section)	Tight	Medium	Tight	Medium	Tight	Ample	Ample	Tight
System choices								
Local		A					B	C
Central								
All-air			(D)	D	D	(D)		
Air and water			E			E		
All-water	F							

SUMMARY

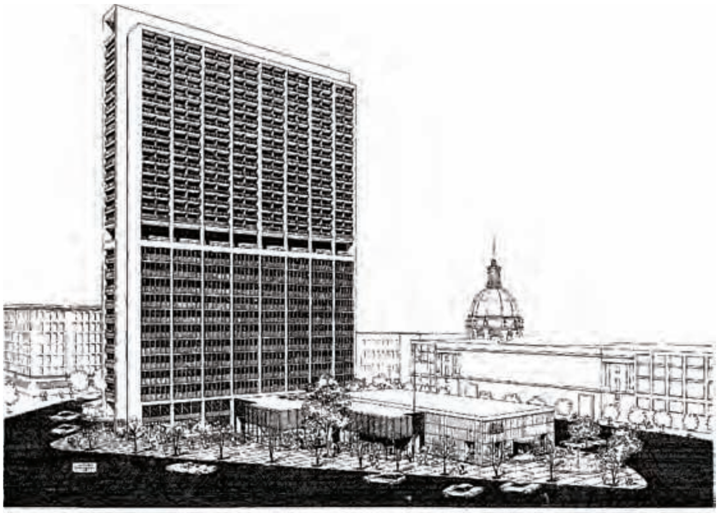
A. The computer center's unique operating schedule and high internal gains usually require a separate system equipped with humidity controls to protect the equipment. Some heat recovery for use in E and F seems possible.
B. The restaurant's special problems of heat, moisture, and aroma, as well as its schedule, require a separate system.
C. The parking area needs only plenty of outdoor air; it requires no thermal tie with the other zones.
D. The cooling-only loads of the interior zones are best served by all-air systems offering control of humidity and air quality. Vertical chase size is tight, however, and high-velocity air distribution may be required. The exterior zones could also be served by all-air systems, but the need for heating, plus the likelihood of outdoor air infiltration and the tight clearance for horizontal ductwork suggest that the system for exterior zones should be independent of the system for interior zones.
E. Quick changes from heating to cooling are best handled by systems with little thermal inertia; some central air quality control is offered by air–water systems.
F. A central all-water system offers energy conservation advantages, recovering waste heat from system D (and potentially from A). Outdoor air is easily and cheaply handled on a local basis, which can also provide cooling.

MECHANICAL SPACE

Probably best located on the top office floor or on a floor of its own between the offices and apartments. Distribution tree sizes will thereby be minimized on the high-rent ground floor.

rarely needed in San Francisco), offices have dual-duct, high-velocity heating/cooling, and commercial (ground-floor) tenants are supplied with hot and chilled water for individual climate control requirements.

As noted, the designers of the Fox Plaza Building selected an intermediate location for the heating and cooling source equipment—as a means of separating floors of apartments from floors of offices. Other typical locations for central equipment are in the basement (where machine noise is most easily isolated, utilities are easily accessed, and machine weight is little problem) and on the roof, where access to air as a sink for rejecting heat is easiest of all, and floor-height is unlimited. Very tall buildings may require several intermediate mechanical floors.



(*a*)

(*b*)

Fig. 12.64 *The Fox Plaza Building, San Francisco. Victor Gruen Associates, Inc., architects and engineers. (a) Elongated façade facing northeast shows the 16 floors of apartments above, the 10 floors of offices below, and the 13th-floor mechanical room—which hosts chillers and pumps for condenser water and chilled water, as well as boilers and converters (steam to hot water) for the fan-coil units in the residential stories above and hot water coils in the office stories below. Air-handling units for the offices are also located here, with air downfed by high-velocity ducts. Residences are heated; offices are heated and cooled. (The cooling tower and the domestic hot water generator–storage units for the residential stories are located on the roof.) (Courtesy of Progressive Architecture.) (b) Photo showing clear vertical distinction between occupancy types. (© Lee Eckert; used with permission.)*

(c) HVAC Systems Integration

Concealment or exposure: The pipes, ducts, and conduits that move necessary resources around a building are often hidden in enclosed spaces unseen by anyone except contractors and repair people. The advantages of concealment include reduced noise broadcasting, fewer complex surfaces requiring cleaning, less care necessary in construction (leaks, not looks, are important), and more control over the appearance of the interior ceiling and wall surfaces. Although maintenance access to such hidden distribution elements is more difficult, various types of readily removable access panels are available, particularly for use with suspended ceilings.

The exposure of distribution networks, however, can provide an honest and direct source of visual interest. Exposure in corridors and service areas and concealment in offices constitutes an approach used in many office buildings. Flexibility is usually encouraged by exposure; changes can be easily made. One of the more spectacular examples of exposed mechanical (and structural) systems is shown in Fig. 12.65—a building resulting from a design competition for a museum of modern art, reference library, center for industrial design, center for music and acoustic research, and supporting services in downtown Paris.

Mechanical–structural integration or separation: The similarity of two technical support systems—structures and environmental controls—has intrigued designers ever since mechanical systems began to require substantial volume for distribution. As the complexity and size of mechanical distribution systems was increasing with technological

Fig. 12.65 A view of the mechanical support systems for the Centre Georges Pompidou, Paris. Piano + Rogers, architects. (© Terri Meyer Boake; used with permission.)

development (typically, more air is required to cool a space than to heat it because of a lower Δt), increasing strength of materials was reducing the size of structural system components. Uncluttered floor areas between more widely spaced columns became desirable for spatial layout flexibility. With

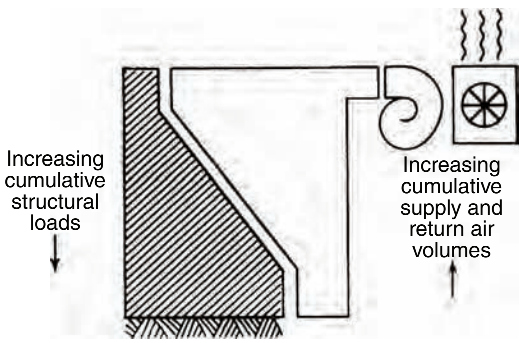


Fig. 12.66 With rooftop central air handling, supply and return air duct sizes decrease as they approach the ground. Conversely, the structural element size increases toward the ground.

mechanical system elements located at or within columns, floor areas remained clear, thus giving mechanical–structural integration further impetus. Locating air-handling units on the roof further encouraged the merging of mechanical and structural systems. One system was growing while the other diminished (Fig. 12.66). Thus, a fixed-column dimension, consisting mostly of the structure at the base and air duct at the top, became possible.

The functions of these two systems, however, differ widely. Compared to the dynamic air, water, and electrical distribution systems, the structural system is static—gravity never ceases. The moving parts in mechanical systems need maintenance far more frequently than the connections of structural components. Changes in occupancy can mean enormous changes in mechanical-electrical systems, requiring entirely different equipment; structural changes of such magnitude usually occur only at demolition. Mechanical systems invite user adjustment; structural systems rarely do.

Thus, although it is possible to wrap mechanical distribution elements in a structural envelope, it is of questionable long-term value, given the differing life spans and characteristics of these systems. The probability of future change suggests that the mechanical system be easily accessible and generally not be embedded in structural elements.

Distribution tree placement options: These options are summarized in Fig. 12.67. Vertical placement decisions are important because they affect floor space allocations, influencing the flexibility of spatial layout and the availability of usable (or rentable) floor space. Horizontal placement decisions affect ceiling height—a particular concern in daylighting design and sometimes a critical factor when building height limits are imposed yet maximum usable floor space is desired. (In Washington, DC, for instance, no building can rise higher than the Capitol.) Vertical and horizontal distribution at the edges of a building can have a dramatic impact on building appearance.

The history of HVAC distribution within high-rise buildings is one of trends and countertrends. Initially, multistory buildings relied upon daylighting and cross-ventilation, so a thin, relatively high-ceiling plan with substantial perimeter was favored. Envelope loads dominated, so perimeter distribution trees (with steam or hot water and of quite small diameter) were generally used. As electric lighting

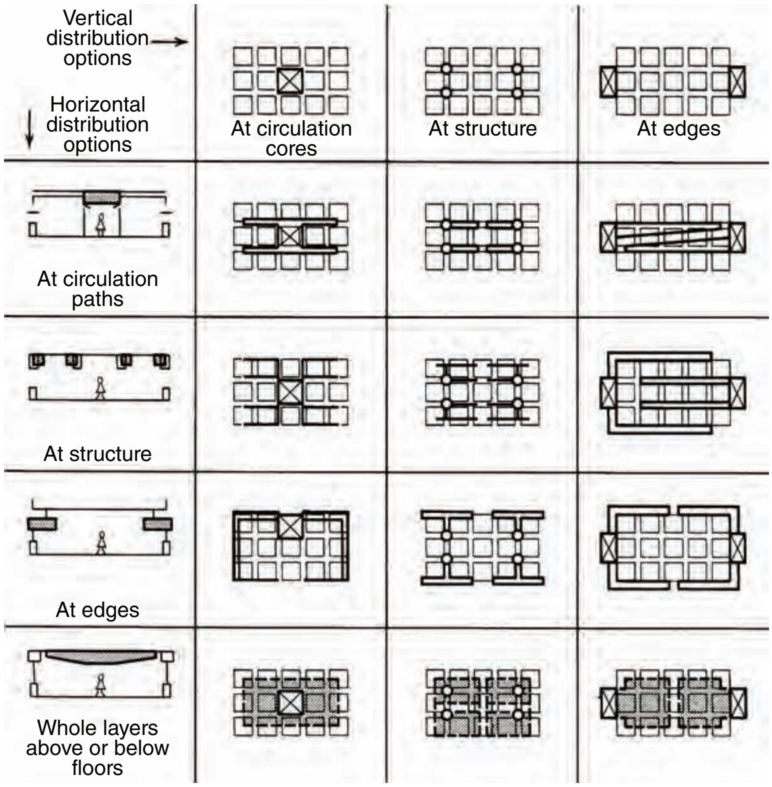


Fig. 12.67 *Distribution tree placement options: vertical (with impact on the plan) and horizontal (with impact on the section). (From class notes developed by G. Z. Brown, University of Oregon.)*

(and thus the need for air conditioning) increased, so did the depth of floor plans; large internal areas needed a lot of cooled air. Central boilers, chillers, and fan rooms were the norm. Thus, bulky air distribution trees appeared. At about the same time, the glass curtain wall and its slick, two-dimensional look of modernity became fashionable. Air distribution trees on the façade were so visually intrusive that they were pushed to the core, where cooling needs were relatively steady. The thin glass-enveloped perimeter, however, experienced extreme heating and cooling loads. Reaching these perimeter areas from vertical distribution trees at the core required larger cavities above suspended ceilings. This pushed the ceiling in the offices down to keep floor-to-floor spacing economical. The result was vast office areas that were visually dull, low-ceilinged, and without daylight.

Current countertrends include decentralized air handling, with small fan rooms on each floor. Vertical air distribution trees are shrinking, horizontal ones becoming more common. At the same time, daylighting is pushing office ceilings higher—as is a preference for indirect lighting and its compatibility with digital display equipment. Night cooling utilizing thermal mass encourages the exposure of concrete structure and favors raised-floor air supply/ventilation systems. A renewed interest in sun control (driven, perhaps, by a quest for high-performance outcomes) is encouraging three-dimensional façades; these are slowly replacing two-dimensional reflective glass façades (which merely redirect solar radiation toward someone else). With increased three-dimensionality at the façade, perimeter distribution trees are once again conceivable.

It is logical to place at the perimeter the parts of the system that deal with the effects of sun, shade, and temperature change in the perimeter zones—leaving at the core a separate network to handle the more stable interior areas. The disadvantages of perimeter distribution include the potential for higher construction costs and the possibility of increased heat gains/losses to/from the distribution systems.

Vertical distribution within internal circulation cores is very common, as it maximizes plan flexibility for the rest of the floor and does not disturb the prized floor areas nearest windows. One centralized vertical distribution trunk, however, will require large horizontal branches near the core. With this choice, early thought must be given to horizontal placement decisions.

An unusual example of vertical air distribution at the core is shown in Fig. 12.68. The unique features of the Fox Plaza office building, Los Angeles, include both fan rooms on each floor *and* a large central vertical air shaft. This air shaft begins at the bottom as a fresh air intake to each floor and tapers to become, at the top, an exhaust air outlet from each floor. The stack effect is utilized to help supply fresh air and to exhaust stale air from this large building, with help from small fans at each floor.

Vertical distribution integrated with structure creates some intriguing possibilities where the idea of integrating structure and HVAC is suitable. Multiple HVAC trees are implied (because there will be multiple columns with which they may be integrated); thus, the horizontal branches tend to be small. These branches, however, often join a vertical trunk at the same place where critical column-to-beam structural connections need to be made; interference is common and can be costly to correct. Vertical distribution at the *edges* is potentially dramatic in form but costly to enclose (if outside) or wasteful of prime floor space (if inside).

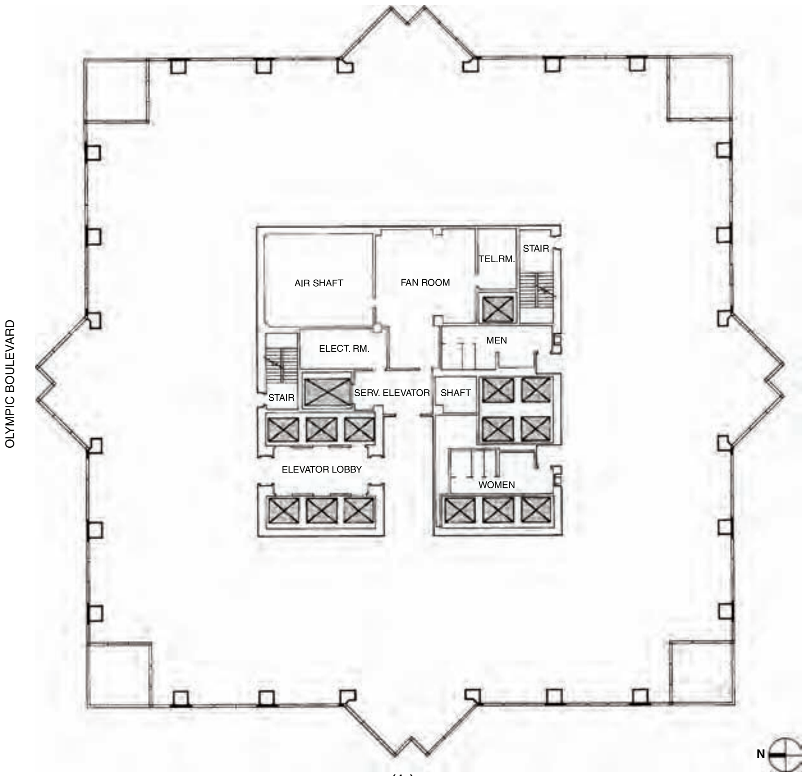
Horizontal distribution above corridors is very common, since reduced headroom in a circulation space is more acceptable than in a main functional area. Furthermore, corridors tend to be placed away from windows, so lower ceilings do not interfere with daylight penetration. Because corridors connect nearly all spaces, supply air access to the spaces is also provided by above-corridor ductwork. Exposure of services above corridors can heighten the contrast between such serving spaces and the uncluttered, higher-ceilinged offices that are served. Horizontal distribution at the *structure* is sometimes chosen, particularly where U-shaped beams or box beams provide ready channels for HVAC distribution. The penetration of horizontal structure members by continuous service runs must, however, be coordinated. Horizontal distribution at the edges can be integrated usefully with sunshading devices and lightshelves; it can also provide a spandrel element that contrasts with the window strips. Horizontal distribution within whole layers below floors (or above ceilings) is often utilized, becoming increasingly common with underfloor air distribution systems.

An example of supply at the edge for both vertical and horizontal distribution is found in the International Building in San Francisco (Fig. 12.69). Vertical shafts are prominently exposed at the corners; these shafts carry supply and return ducts serving the four perimeter air-conditioning zones. Air-handling equipment and a 750-ton (2640-kW) chiller plant are located on the floors just below the terrace level (least desirable for rental). Each corner duct branches to serve two zones. Pressure reduction and blending are handled by equipment located above the hung ceiling; from these points, air flows to strip diffusers directly above the glass on the four sides of the building. Abundant control zones offer comfort to personnel in each area.

Interior zones on each floor are supplied by a riser duct in the building core, which branches at each floor to a loop just outside the line of elevators. The loop serves ceiling diffusers. Between the perimeter loop and the interior loop, a return loop collects air for return to the central station air-handler (second and third floors). The return loops on the 11th to 21st floors are picked up by external return risers on alternate exterior corners. From the 10th floor down, the loops are picked up (as shown in Fig. 12.69) by an interior return riser that extends down through the core in front of the blank faces of the high-rise elevators. To provide a clear space between the elevator banks on the main floor (fourth or terrace), the two core duct risers are offset at the ceiling of that story.

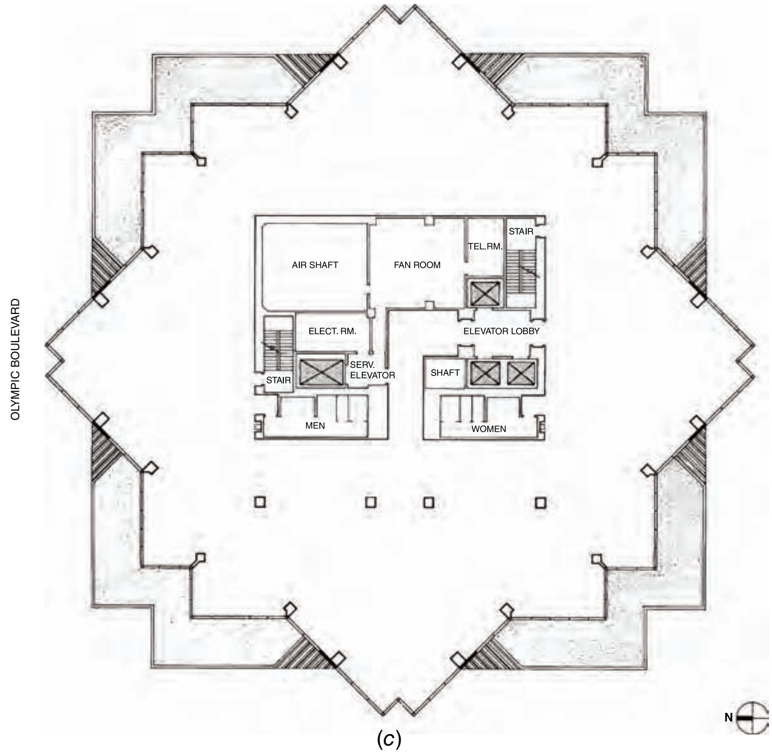
In summary, perimeter-area air for all stories is supplied through corner ducts. Central-area air for all stories is supplied through a core duct. All return air above the 10th floor is carried down through the return ducts at the *other* two corners. Return air from the 10th floor and below is carried down by a return duct in the core.

(*a*)

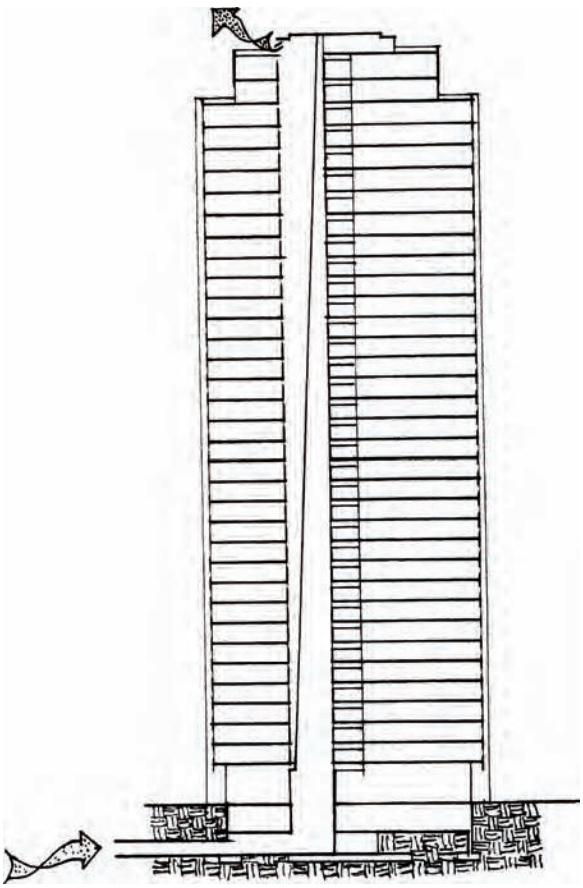


(*b*)

Fig. 12.68 *The Fox Plaza office building in Los Angeles is a 34-story, 800,000-ft² (74,320-m²) granite and glass tower (a) with an unusual vertical distribution tree. (b) Typical lower-floor plan (floors 6 to 16) shows both a fan room and a large vertical air shaft. At this lower level, most of the shaft area is supplying outdoor air (from an intake in the bluff face below the building); the remainder is exhausting stale air toward the roof. Note the lack of columns between the core and perimeter, contributing to office layout flexibility. (c) Typical upper-floor plan (floors 31 to 33) shows fewer elevators; by this level, most of the shaft area is exhausting stale air toward the roof. (d) Section shows the tapered interior of the constant-cross-section central air shaft, which relies upon the stack effect to bring in (usually cooler) outdoor air at the base and expel hotter exhaust air at the top. (Courtesy of Johnson Fain Pereira Associates, Architects, Los Angeles, and Kim, Casey and Harase, Inc., Engineers, Los Angeles. Photo by Wolfgang Simon.)*



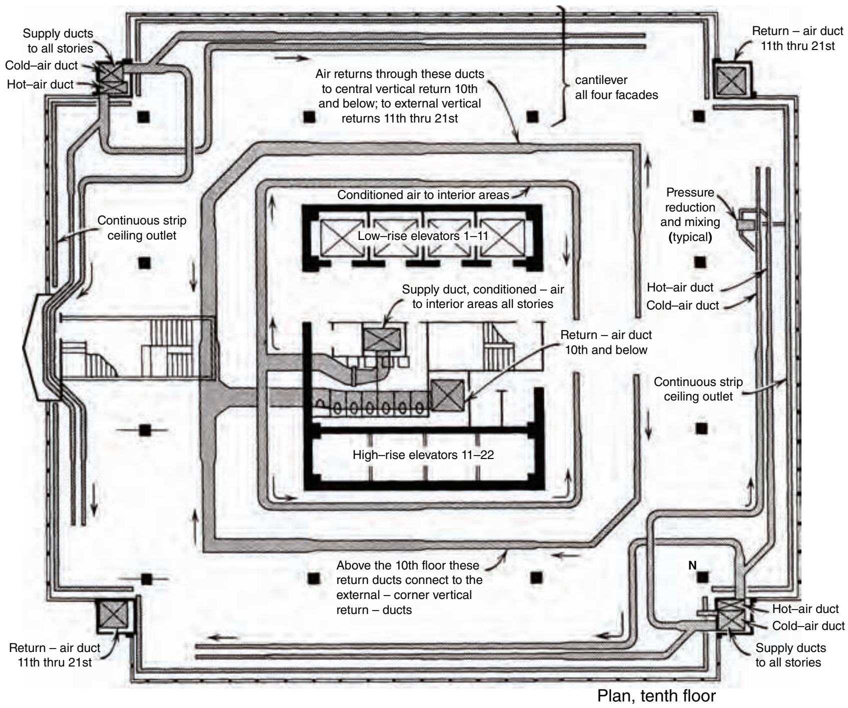
(*c*)



(*d*)

Fig. 12.68 *(Continued)*

(*a*)



(*b*)

Fig. 12.69 *The International Building, San Francisco. Anshen and Allen, architects; Eagelson Engineers (Charles Krieger, E.E.), mechanical designers. (a) Photo of one of the four corner main duct enclosures. (b) Tenth-floor plan. Column bay spacing is 24 ft, 6 in. (7.5 m), with a 16-ft (4.9-m) cantilever on all four façades. The major supply ducts (both hot and cold) to all 21 floors are located in two opposite corners. Each of these supply distribution trees serves two adjacent sides of perimeter offices. The conditioned air is supplied from a third-floor mechanical space. In the opposite two corners, return air from the upper 11 floors is collected and taken down to the mechanical space. The remainder of the return air is taken down through the core. (Courtesy of Progressive Architecture.)*

12.17 HVAC SYSTEMS FOR SMALL BUILDINGS

Several examples of HVAC systems applied to smaller buildings (or larger buildings employing local systems) are provided in this section. These systems do not represent all possible small-building HVAC arrangements—by a long shot. Designers are amazingly creative and come up with many, many solutions to similar problems. HVAC system selection is also heavily driven by context—fuel availability and cost, owner desires, local norms, and the like.

(a) Local Systems

Gas-fired baseboard heaters: Using natural gas or propane, these devices might be employed where only space heating is required. The units heat by convection and by radiation (as is also the case for electric baseboard units). At a steady-state efficiency of 80%, these gas-fired units use a lower-grade resource (compared to electricity) to accomplish this simple thermal task. They are direct vented (using a built-in fan) to the outside, and therefore must be installed on or near an exterior wall; vents are 1½ in. in diameter, with a maximum length of 19 in. (38 mm in diameter, 483 mm in length). With a cross section of 9 in. high by 5 in. deep (230 mm × 130 mm), a 48-in. (1220-mm) length will deliver 5800 Btu/h (1700 W); a 72-in. (1830-mm) length will deliver 9400 Btu/h (2755 W). This is a local system.

Unitary air conditioners: The device shown in Fig. 12.70 is perhaps the most commonly seen piece of mechanical equipment in the United States. Usually perched in windows in full view of passersby, these packaged air conditioners noisily remind us that many of our buildings still are *not* centrally cooled (active cooling was considered a luxury until long after World War II).

Built-in, through-wall air conditioners offer a low-first-cost way to provide thermal zoning for individual apartments, motel rooms, and the like. As a local system of low capacity, these units are generally not as energy efficient as would be the

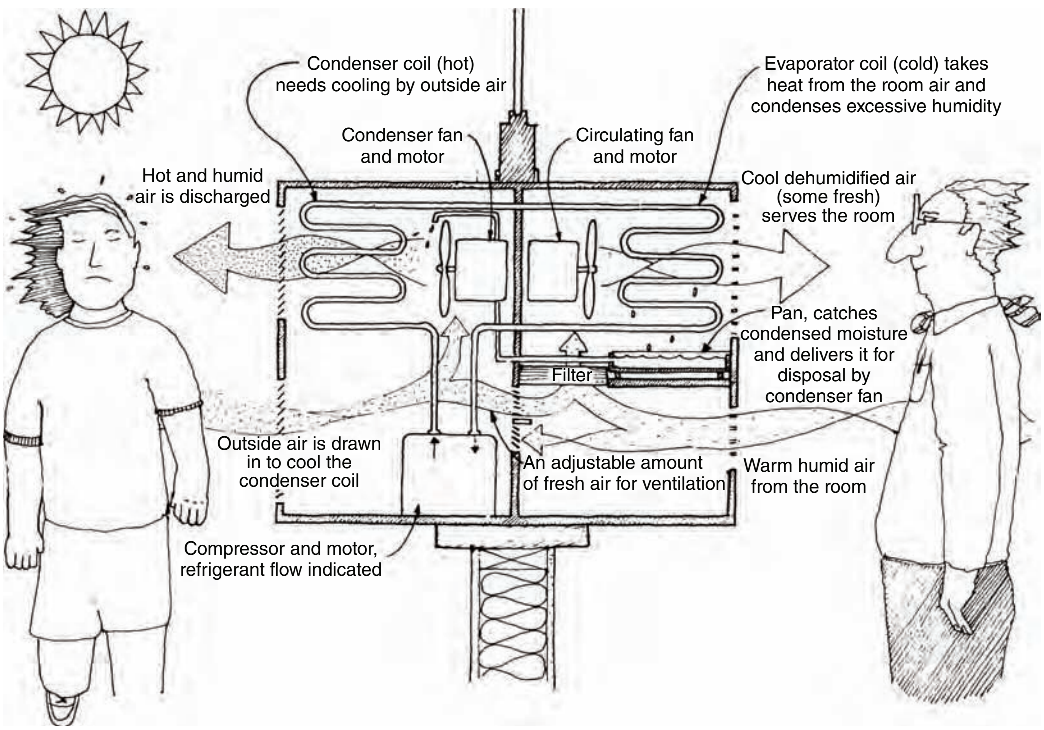
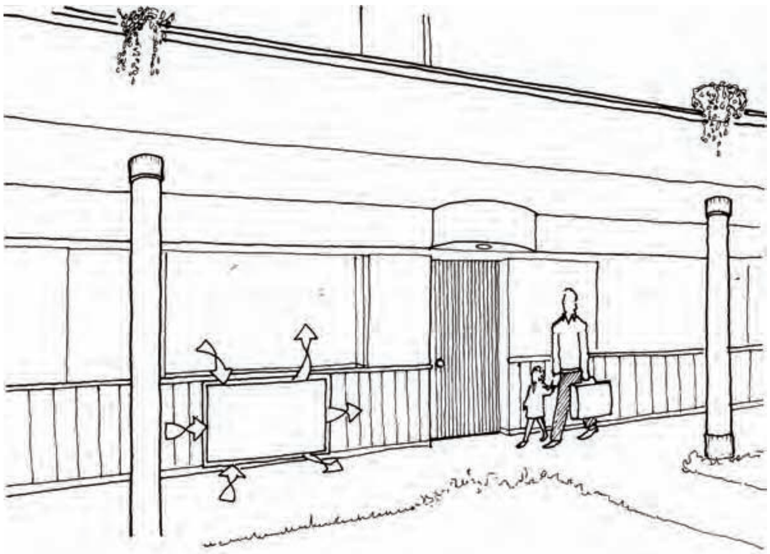


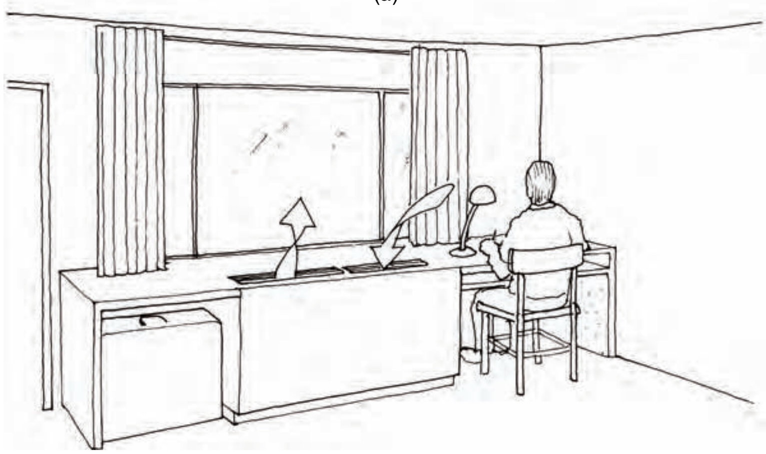
Fig. 12.70 *Diagram of a typical through-the-wall air-conditioning unit. The unit is self-contained, requiring access to outdoor air and electricity to power the compressor and the two fans. Typical capacities are 1 to 2 tons (12,000 to 24,000 Btu/h [3.5 to 7 kW]).*

case with larger central equipment. However, if turned on only when cooling is needed (i.e., when people are present), they can provide substantial savings over a larger always-on system. Properly operated local systems can be energy efficient over time—the key word is "properly."

Local air–to-air heat pumps: The use of individual (local) units is especially common in building types with all-perimeter spaces with varying orientations, numerous thermal zones, and a penchant for personal "ownership" of space. Motels are a prime example. In Fig. 12.71, separate air–air heat pumps serve each motel room; at best, their constant noise helps mask the intermittent sounds from the adjacent parking lot/circulation space. Each customer controls his/her own climate (for better or worse, from an energy standpoint). If a central water loop replaced outdoor air as the heat source/sink, energy use and life-cycle cost would go down, although the first cost would increase.



(*a*)



(*b*)

Fig. 12.71 *Air-to-air heat pumps serve a motel. (a) A panel set just forward of the exterior wall allows the heat pump to intake and exhaust outdoor air around the panel edges. When cooling, the unit discharges warm air; when heating, cool air. (b) Interior cabinet contains the heat pump. Room air is taken in as shown, then discharged (after cooling or heating) upward across the glass surface—the likely point of maximum heat loss or gain.*

Electric resistance heaters: These common devices have some impressive plusses; they are very low first cost and easily provide individual thermostatic control (making each room a separate heating zone). On the other hand, they bear the disadvantage of using high-quality energy to do a simple thermal task (resulting in poor exergy performance). Although electric resistance heating can legitimately be said to have an efficiency of 100% on site, the losses inherent to electrical generation and distribution drop the efficiency to around 35% when viewed from the perspective of the source. Because this is a local system, good operations habits can save energy if unused rooms remain unheated. A few of the many types of electric resistance heaters are shown in Fig. 12.72. As in the case of metal wood stoves, surfaces can sometimes reach high temperatures, requiring care in the location of heaters relative to furniture placement, draperies, traffic flow, and children. Electric heaters are sized by their capacity in kilowatts (1 kW = 3413 Btu/h). The maximum allowable power density is around 250 W per linear foot of heater (820 W per linear meter).

Radiant ceiling with electric resistance: A ceiling can be constructed to include electric resistance via wiring (Fig. 12.73). Because the ceiling is not touched by occupants, it can be safely heated to a rather high temperature. The primary disadvantage of ceiling-based heat is that hot air stratifies just below the ceiling, so that air motion is discouraged. Remember also that Chapter 4 suggests more discomfort with a warmer ceiling. With wiring hidden within the ceiling surface, unwary occupants can damage wires while installing hooks or light fixtures.

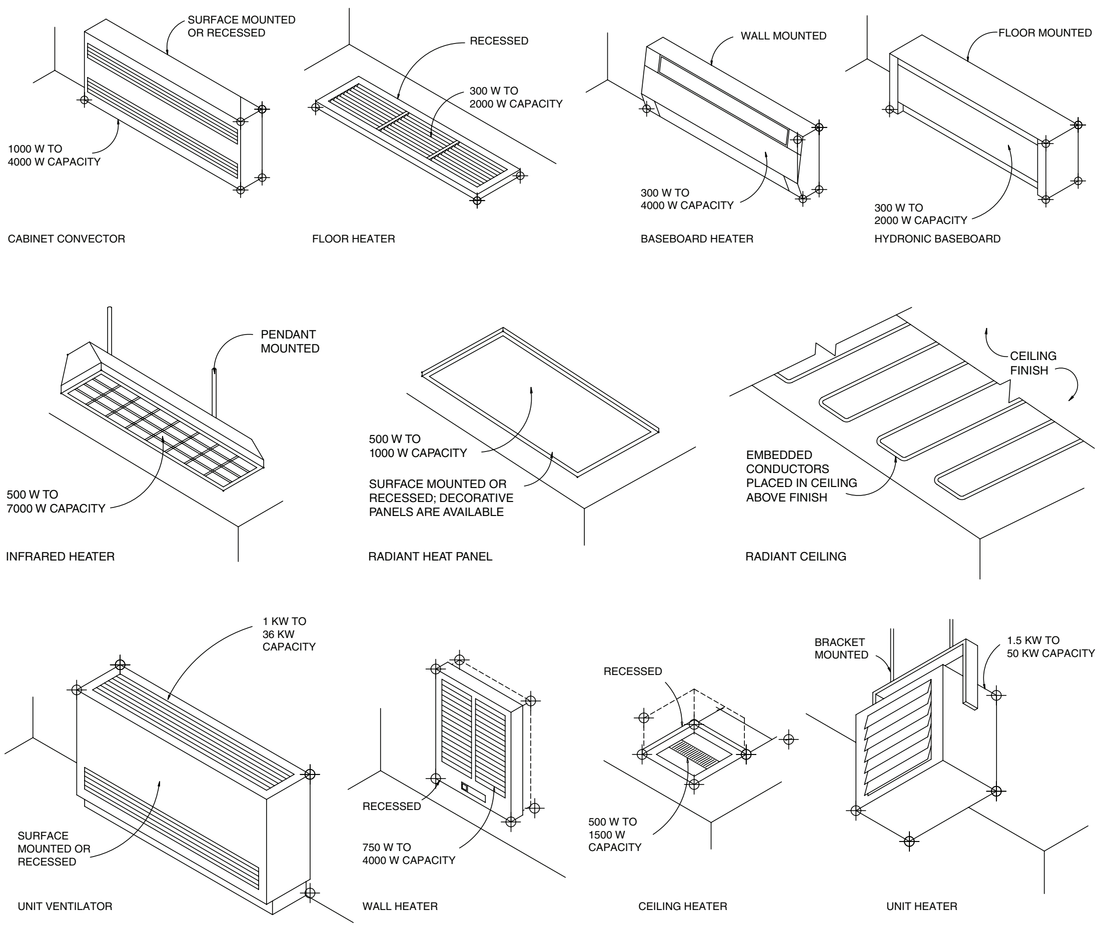


Fig. 12.72 *Varieties of electric resistance heating units. (Reprinted by permission from AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 10th ed.; © 2000 by John Wiley & Sons, Inc.)*

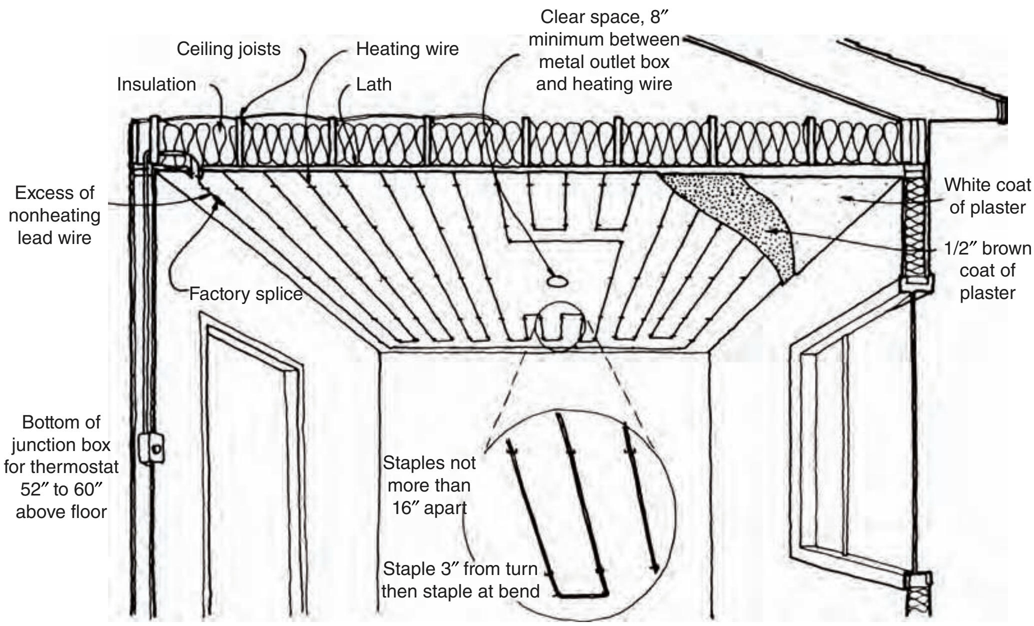


Fig. 12.73 *Radiant heating electrical cable is installed prior to completion of a plaster ceiling.*

(b) Central Systems

Hot water baseboard and radiator systems: Hot water heating circuits that serve baseboards or radiators come in four principal arrangements. Figure 12.74*a* shows a series loop system, usually run at the building perimeter. The water flows to and *through* each baseboard or radiator in turn. As a result of this series flow, the water at the end of the circuit is a little cooler than at the start—but because the water temperature drop in a residential hot water system seldom exceeds 20F° (11C°), the average water temperature can usually be used to select the baseboard or other elements. Valves at each heating element are not possible, because any valve could shut off the entire loop. Control is by damper adjustment at each baseboard, which reduces the natural convection of air over the fins. This is a one-zone central system—all elements are on, or off, together. There is no general rule about the maximum allowable length of a water circuit, but for long runs, pipe size can be increased or several loops used in parallel to create more than one thermal zone.

The one-pipe system shown in Fig. 12.74*b* and Fig. 12.75 is a very popular option. Special fittings act to divert part of the water flow into each baseboard. A valve may be installed at each unit to allow for reduced heat output or for a complete shutoff to conserve energy—an advantage that the series loop system does not provide. The one-pipe system uses a little more piping and thus is not as economical to install as the series loop system, in which piping is minimal. Again, the supply water temperature will be lower at the end of the run than at the beginning.

The two-pipe reverse–return layout shown in Fig. 12.74*c* provides the same supply water temperature to each baseboard or radiator, because (unlike a series system) supply water is not cooled by passing through a previous baseboard or by the addition of return water (as in a one-pipe system). Equal friction loss, resulting in equal flow, is achieved through all baseboards (numbers 1 to 5) by *reversing* the return instead of running it directly back to the boiler. This equality is accomplished by having equal lengths of water flow through any baseboard unit together with its lengths of supply-and-return piping. More pipe is required for this system than for the systems shown in Fig. 12.74*a* or 12.74*b*.

Figure 12.74*d* shows an arrangement that is not usually favored because the path of water through baseboard number 1 is much shorter than

THERMAL CONTROL

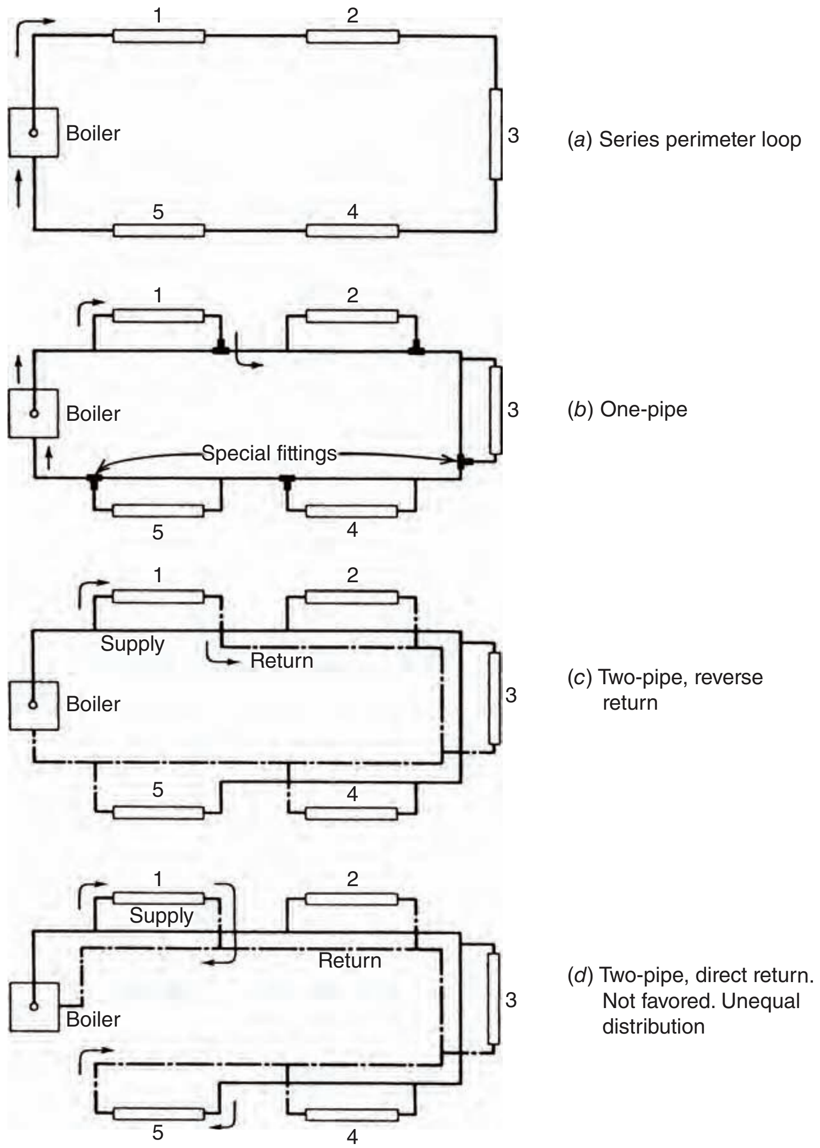


Fig. 12.74 *Diagrams of hydronic distribution options (a, b, c, d), seen in plan view. Baseboard convector delivery devices are suggested here. Controls are not shown.*

that through the others, especially number 5. Baseboard number 5 could easily be undesirably cool, because it is short-circuited by the others.

Control of pipe expansion requires expansion joints in long runs of pipe and clearance around all pipes passing through walls and floors. Each time a hydronic system changes from room temperature to its heated condition, the piping will undergo the expansion shown in Table 12.7, assuming a 70°F (21°C) initial temperature.

An air cushion tank, compression tank, or expansion tank is a closed tank containing air and is usually located above the boiler. When water in a hydronic system is heated, it expands, compressing the air in the tank. This allows for operation in the usual range of system temperatures, including

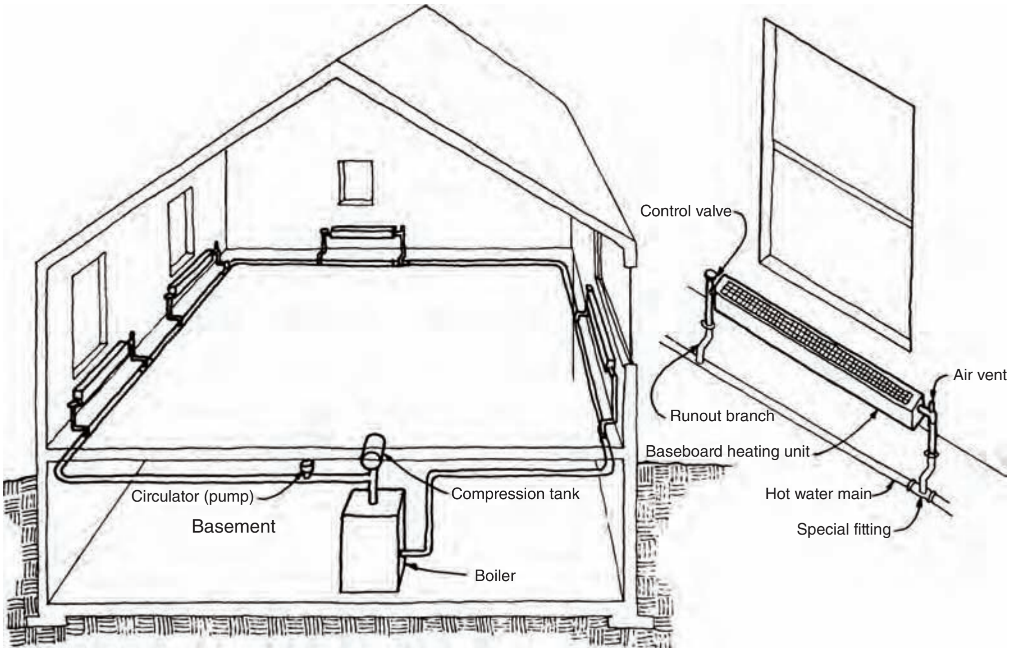


Fig. 12.75 One-pipe hydronic system.

temperatures above the usual boiling point of water, without the frequent opening of the pressure relief valve. One type of air cushion tank, called a diaphragm tank, separates the air and water with an inert, flexible material; this prevents reabsorption of air by the water. For a conventional (unpressurized) air cushion tank, allow 1 gallon of tank capacity for every 5000 Btu/h (1 L for every 385 W) of total system heat capacity. For a pressurized tank (at least 8 lb/in^2 [55 kPa]), allow 1 gallon of tank capacity for each 7000 Btu/h (1 L for each 540 W), or see the manufacturer's recommendations.

Air vents and water drains are part of the water distribution system. Except for the necessary air cushion in the upper part of the compression tank above the boiler, air must not be allowed to accumulate at high points in the piping or at the baseboard or convector branches. Air vents at all high points relieve possible air pockets that would otherwise make the system air-bound and inoperative.

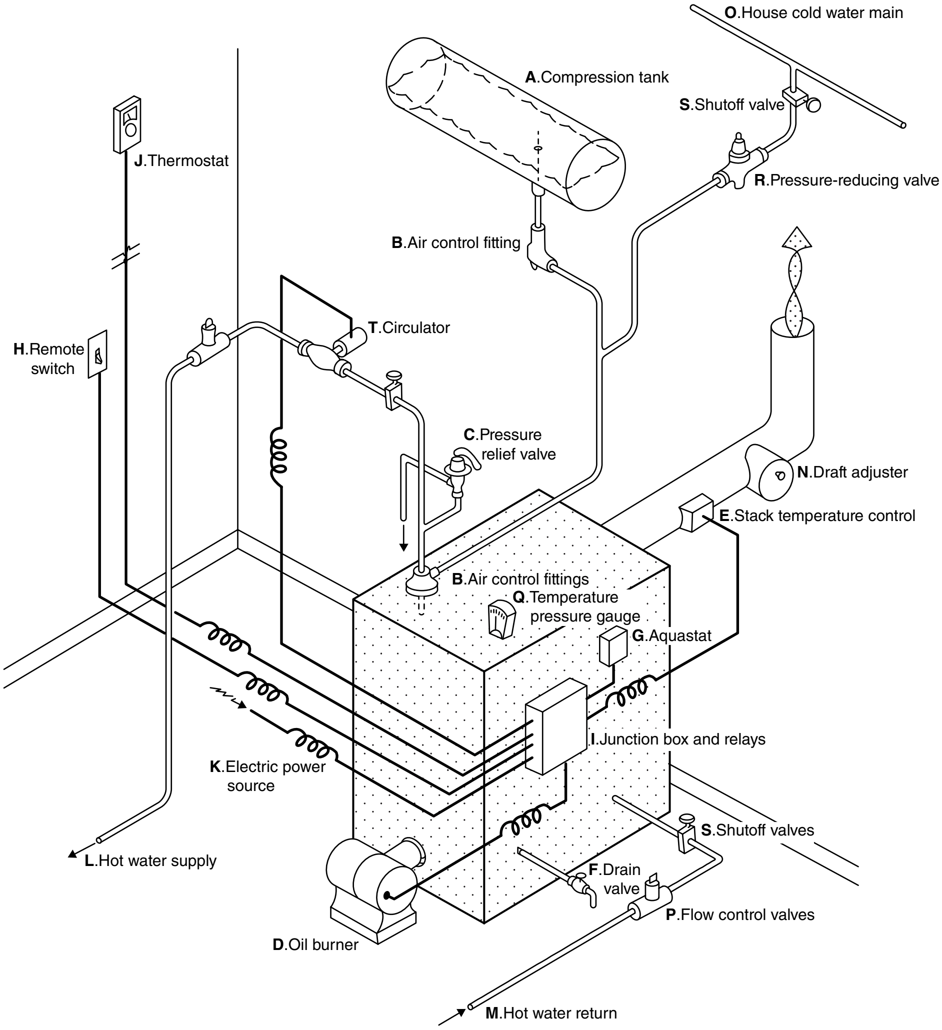
If a system is drained and left idle in a cold building, water trapped at low points can freeze and burst the piping or fittings. Operable drain valves must be provided at such locations and at the bottom of the boiler, as shown in Fig. 12.76.

Hydronic and electrical controls allow for automatic system operation, described in Fig. 12.76. There are two options for system control:

1. As in Fig. 12.76, the thermostat controls the circulating pump and the boiler. In colder weather, the system operates almost continuously, and the average temperature in the system gradually rises.

TABLE 12.7 Expansion in Copper Tube and Iron Pipe

Pipe Expansion, in. per 100 ft (mm/100m)		
Water Temperature °F (°C)	**Iron Pipe**	**Copper Tubing**
160 (71)	0.7 (58)	1.0 (83)
180 (82)	0.9 (75)	1.3 (108)
200 (93)	1.0 (83)	1.5 (125)
220 (104)	1.2 (100)	1.7 (142)



(A) *Compression tank*. Accommodates the expansion of the water in the system.
(B) *Air control fittings*. Vent out unwanted air in the boiler and maintain the level in the compression tank.
(C) *Pressure relief valve*. Usually set for 30 psi. Initial cold pressure about 12 psi. Relieves excessive system pressure.
(D) *Oil burner*. Responds to aquastat or thermostat.
(E) *Stack temperature control*. Senses stack temperature and stops oil injection if ignition has not occurred.
(F) *Drain valve*. At low point in the water system.
(G) *Aquastat*. Maintains temperature of boiler water by starting the oil burner when temperature of water drops below the aquastat's setting. Sometimes set at about 180 F.
(H) *Remote switch*. At a safe distance from the boiler so that the plant can be turned off in case of trouble during which the boiler cannot be approached.
(I) *Junction box and relays*. General control center.
(J) *Thermostat*. When the room temperature drops below its setting, it turns on both the oil fire and the circulating pump.
(K) *Electrical power source*. Operates from a separate individual circuit at the power panel.
(L) *Hot water supply*. Copper tubing to convectors or baseboards.
(M) *Hot water return*. Copper tubing from convectors or baseboards.
(N) *Draft adjuster*. Regulates the draft (combustion air) over the fire.
(O) *House cold water main*. From which water is fed automatically into boiler.
(P) *Flow control valves*. Prevent casual flow of water by gravity when the circulator is not running.
(Q) *Temperature pressure gauge*. Indicates water temperature and pressure. Sometimes supplemented by immersion thermometers in supply and return mains.
(R) *Pressure-reducing valve*. Admits water into the system when the pressure there drops below about 12 psi. Has a built-in check valve to prevent backflow of boiler water into the water main.
(S) *Shutoff valves*. Normally open. Can be closed to isolate the system and permit servicing of components.
(T) *Circulator*. Centrifugal circulating pump that moves the water through the tubing and heating elements.

Fig. 12.76 *An oil-fired boiler and its hydronic and electrical controls.*

2. The thermostat controls only the boiler, and the circulating pump operates continuously. This uses more energy for the pump but minimizes system temperature variation and thus the possibility of expansion noises.

Makeup water is added as required, the air level in the tank is regulated by the air control fittings, and the circulator and burner operate as controlled by the aquastat and thermostat. If air vents in the piping are not automatic, they will require periodic manual "bleeding" of unwanted air. Circulating pumps are used to overcome the friction of flow in the piping and fittings and to deliver water at a rate sufficient to offset the hourly heat loss of the building. Pipe insulation is required whenever the pipes are outside the heated envelope of the building; ASHRAE Standards 90.1 and 90.2 specify insulation appropriate to the design water temperature.

Sizing of a hydronic heating system: Calculations for the sizing of a water distribution system are based upon consideration of the required flow and the desired friction loss in the piping. For an open-loop domestic water supply system, another factor is the vertical distance the water must be raised. In a closed-loop heating system, however, the weight of the cooler water returning to the boiler essentially counterbalances the weight of the hot water being raised upward.

The key to pipe sizing is the overall required flow rate. Ordinarily, the temperature drop that occurs as the hot supply water transfers heat to the space (through a convector) is about 20F° [11C°] in residences; in commercial applications, 30, 40, or 50F° (17, 22, or 28C°) temperature drops are also common, as recommended by the manufacturer of the baseboard or convector. Because the entire design building heat loss is overcome by this system, in I-P units, total flow rate, gpm

$$= \frac{\text{design heat loss, Btu/h}}{20\text{F}° \times 60 \text{ min/h} \times 8 \text{ lb/gal} \times 1 \text{ Btu/lb F}}$$

$$= \frac{\text{design heat loss}}{9600}$$

In SI units, total flow rate, L/s

$$= \frac{\text{design heat loss, W}}{11\text{C}° \times 1 \text{ kg/L} \times 4180 \text{ W sec/kg C}°}$$

$$= \frac{\text{design heat loss}}{45{,}980}$$

Friction loss through piping and fittings can be accounted for using the procedures shown in Section 19.11, and the main supply and return pipes can be sized. The same procedure can be applied to branches, proportioned to the heat they must deliver. The total friction to be overcome in the most distant run is then converted from total psi to *feet of head*, with each foot of head = 0.433 psi (the pressure exerted by a foot-high column of water). In SI, 1 ft of water = 2.99 kPa.

A pump can be selected with the friction loss of the system expressed in feet of water (or head) and the flow rate established. Figure 12.77 shows typical performance curves for four pumps. The designer enters the curve with a desired flow rate, then selects the pump with a head capacity greater than or equal to the head required. Pump performance curves are provided by the manufacturer.

The critical design choice, however, is not pipe size. It is relatively easy to distribute small-diameter pipes within typical building constructions. Rather, the critical choice is the hot water supply temperature: The higher this temperature, the smaller the convector units that deliver heat to each space. Higher temperatures, however, can endanger occupants, who may suffer burns if they touch exposed parts of the convectors or the piping. Higher temperatures also can lead to steam within the boiler or distribution tree—although the system is under pressure and the boiling point

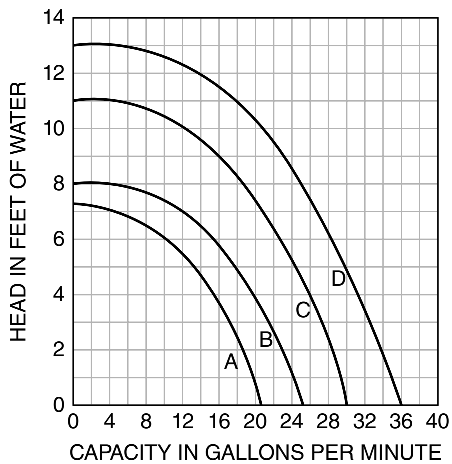


Fig. 12.77 *Typical pump performance curves for four pumps used in hydronic heating systems. One foot of water = 2.99 kPa; 1 gpm = 0.0631 L/s. (Courtesy of the Hydronics Institute Division of GAMA, Berkeley Heights, NJ.)*

TABLE 12.8 Hydronic Baseboard Convectors

Water Supply					
Temperature		Flow Rate[a]		Heat Delivered per Unit Length[b]	
°C	°F	L/s	gpm	Watts/m	Btu/h ft
60	140	0.06	1	307	320
		0.25	4	326	340
66	150	0.06	1	365	380
		0.25	4	384	400
71	160	0.06	1	432	450
		0.25	4	461	480
77	170	0.06	1	490	510
		0.25	4	518	540
82	180	0.06	1	557	580
		0.25	4	586	610
88	190	0.06	1	614	640
		0.25	4	653	680
93	200	0.06	1	682	710
		0.25	4	720	750
99	210	0.06	1	739	770
		0.25	4	778	810

Source: Slant/Fin Ltd. Mississauga, Ontario.

[a]Use flow rate of 0.6 L/s (1 gpm) unless flow rate is known to be ≥0.25 L/s (4 gpm).

Pressure drop is as follows: flow 0.6 L/s (1 gpm) = 3.76 mm/m (0.045 in./ft).
flow 0.25 L/s (4 gpm) = 42 mm/m (0.5 in./ft).

[b]Baseboard finished length will be 76 mm (3 in.) longer than the length required to meet the heating need.

is therefore greater than 212°F (100°C). These systems are not designed to accommodate steam, and serious injury can sometimes result. A safe choice for average water distribution temperature is 180°F (82°C), even though this results in larger convectors. A slightly lower annual average energy consumption should accompany a lower distribution temperature.

Baseboard convectors will be selected from manufacturers' data tables, such as the one shown in Table 12.8. Two common baseboard types are RC (usually cast iron with a water-backed front surface and an extended rear heating surface) and finned tube (a metal tube with an extended surface in the form of fins, usually placed behind a metal enclosure).

EXAMPLE 12.3 What length of baseboard convector (Table 12.8) is necessary along a 20-ft-long [6-m-long] living room wall? From calculations, the living room heat loss is 9000 Btu/h (2635 W). The average water temperature is 180°F (82°C), and water flow is about 1 gpm (0.6 L/s).

SOLUTION

With 180°F supply water and 1 gpm flow rate, Table 12.8 shows that 580 Btu/h will be delivered for each linear foot of baseboard convector; 9000 Btu/h ÷ 580 Btu/h ft = 15.5 ft. Choose a baseboard combination of 16-ft overall length, consisting of two 8-ft (finished length) pieces. The total active finned length will be about 15.5 ft. ■

Hydronic radiant floors: This heat delivery approach has several comfort advantages over radiant ceilings. The system components are largely the same as with a baseboard or radiator system, except that coils of pipes replace individual radiators or baseboards. A balancing valve should be installed on each coil. Where uninsulated spaces underlie floors (or are located above radiant ceilings), special attention should be paid to adequate insulation; a radiant panel will generate especially high temperatures, and thus a very high Δt through the floor.

Thanks to better insulation, modern buildings often require radiant panels that are smaller in area than the floor (or ceiling) area available. In a conventional radiant panel system, the panel is placed nearest the exterior walls, where the heat loss is greatest. In a solar-heated building, this is not so clear. If the panel heats the floor surface just inside south-facing glass, how much warming will be left to the sun? A preheated slab will absorb much less solar radiation. However, in cloudy cold weather, the area closest to the south glass could become uncomfortably cool.

In the past, copper tubing was widely used for the heating coils. This typically required a number of connections within a coil, and each connection represented a potential point of failure over the life of the panel. Today, coils are typically one-piece and are made of plastics such as cross-linked polyethylene tubing. When the floor is concrete or other cast-in-place material, the coil is either directly embedded in the slab (tied down to resist floating during the pour) or stapled to an underfloor, over which the slab is poured. Radiant floors involving coils placed underneath wood floors are increasingly popular.

Rugs or carpets over radiant floors are a mixed blessing; they are soft on the feet but interfere with the exchange of heat. Special undercarpet pads can facilitate heat transfer; higher water temperatures can be used in the coils, because skin contact with the floor is prevented by the carpet.

Panel (radiant ceiling or floor) heating design usually depends on a water temperature of 120°F (49°C) for floors and 140°F (60°C) for ceilings. An uncarpeted concrete floor slab using ¾-in.-diameter pipe or tube on 12-in. centers (20-mm diameter on 300-mm centers), with an average water temperature of 120°F (49°C), will deliver 50 Btu/h ft^2 (158 W/m^2) of floor panel. A ceiling panel with nominal ⅜-in. tube on 6-in. centers (10-mm diameter on 150-mm centers), with an average water temperature of 140°F (60°C), will deliver 60 Btu/h ft^2 (189 W/m^2) of ceiling panel.

To determine the required area of heated panel, divide the room's design heat loss by the rate of panel heat delivery. Although radiant ceilings deliver more heat per unit area, they also discourage air motion because the warmest air rises to lie against the warmest surface. In contrast, at a radiant floor the coolest air drops to contact the warmest surface, is then warmed, and rises to be cooled at the ceiling, drops to the floor, and repeats this cycle continually.

Each radiant panel contains one or more coils. In floor panels, each coil typically delivers 10,000 Btu/h (2930 W) and should be no longer than about 200 linear feet (60 m). In ceiling panels (with smaller-diameter tubes), each coil delivers around 3000 Btu/h (880 W) and should be no longer than about 100 linear feet (30 m).

Sizing of the main pipes and pump is based upon the longest circuit, measured along the length of the supply pipe from the boiler to the coil and back along the return line to the boiler. Two guidelines apply:

1. Do not include the length of the coil itself in this circuit length.
2. No section of a floor panel main pipe should be less than ¾ in. (20 mm) in diameter.

EXAMPLE 12.4 Determine the panel area and coils required for a radiant floor in a living room 15 ft × 25 ft (= 375 ft^2) with a design heat loss of 12,000 Btu/h (4.6 m × 7.6 m = 34.8 m^2, heat loss 3514 W).

SOLUTION

The required panel area is

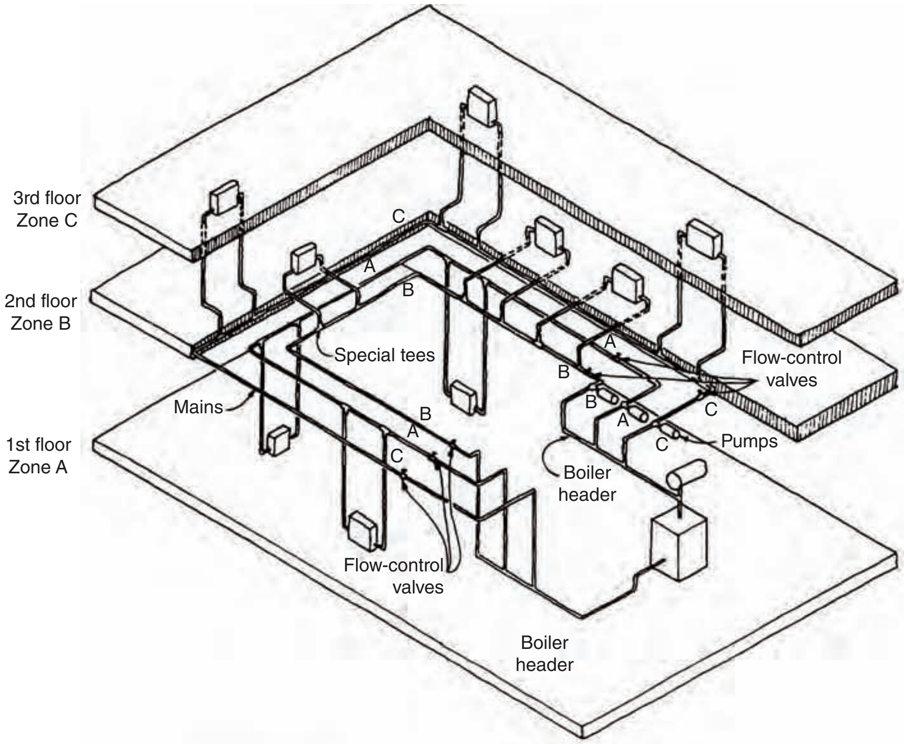
$$\frac{12{,}000 \text{ Btu/h}}{50 \text{ Btu/h ft}^2} = 240 \text{ ft}^2 \text{ of floor panel}$$

The room has 375 ft^2 of floor available. The heated panel is usually placed along the exterior walls, where the room heat loss is greatest (unless solar heat through south windows is involved). The number of coils in the panel is

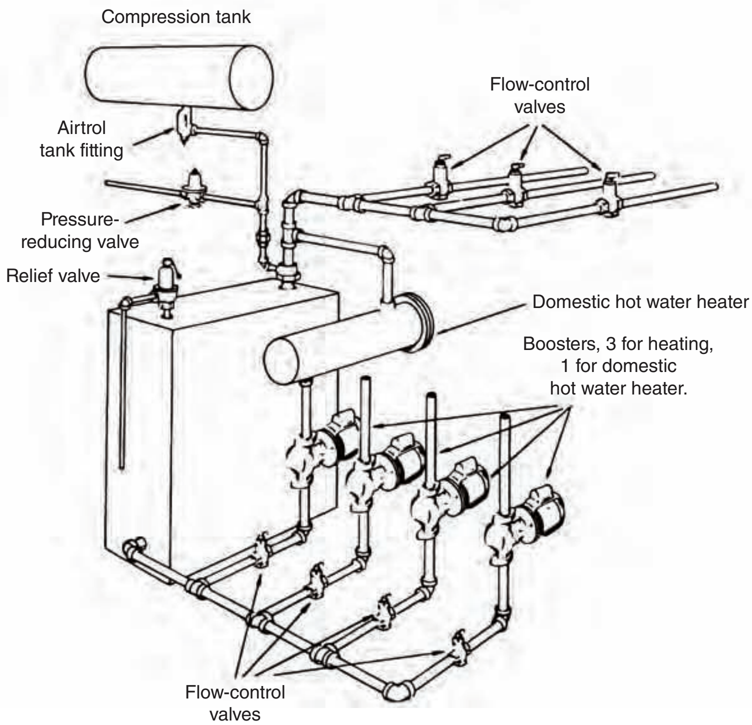
$$\frac{12{,}000 \text{ Btu/h}}{10{,}000 \text{ Btu/h per coil}} = 1.2 \text{ coils}$$

Use one coil in this panel. ■

Hydronic system zoning: Figure 12.78 shows that zoning is relatively easy to accomplish with hydronic systems. The building shown in the schematic diagram has three separately heated areas—the first, second, and third floors. Each floor can be heated to different temperatures as called for by thermostats in the separate apartments. For example, if only the thermostat serving the second floor (zone B) calls for heat, it turns on pump B. Flow-control valves B open, admitting hot water from the boiler to piping circuit B. Flow-control valves A and C remain closed, preventing flow in circuits A and C. Any or all of the zones may operate at one time. The boiler keeps a supply of hot water continually ready



(*a*)



ITT Bell and Gossett

(*b*)

Fig. 12.78 *Three-zone, multicircuit, one-pipe system. (a) Each convector has connections to the one pipe. (b) Boiler, piping, and water controls suitable for this three-zone, one-pipe system. Each one-pipe circuit should be provided with two flow-control valves and a circulator (also called a booster or pump) on the supply (or return) pipe. (Courtesy of ITT Bell and Gossett.)*

to supply any zone on demand. This is achieved by an aquastat immersed in the boiler water. When the boiler water drops below the prescribed temperature, it turns on the firing device, such as an oil burner or a gas burner, which brings the water up to the temperature setpoint.

Two famous residences in the U.S. Midwest utilize hydronic systems. Frank Lloyd Wright's Robie House (Chicago) has wall radiators integrated below the north windows in the living room. Underfloor radiators with grilles in the floor were to be provided below the full-height south windows, but were apparently never installed. The boiler sits in a basement room. Mies van der Rohe's Farnsworth House (Fox River, Illinois) preserves its four walls of ceiling-to-floor glass by concealing radiant heating pipes in the floor slab. The boiler sits within a central utility "closet."

Modern radiators are designed to reflect the sleek and simple lines of contemporary architecture and are getting new exposure with some colorful products (Fig. 12.79). The Mayer Art Center at Phillips Exeter Academy in New Hampshire (Fig. 12.80) features new exposed radiators in older buildings. These radiators are based on simple components (typically, 2¾ in. [70 mm] wide) that can be combined in many heights and widths, inviting the designer to feature them rather than to hide them in metal cabinets.

Warm air heating systems: About a century ago, these systems began to supersede open fireplaces in residences. A typical early system involved an iron furnace that stood in the middle of the basement and was hand-fired with coal. Surrounding it was a sheet-metal enclosure. An opening in its side near the bottom admitted cool combustion air that gravitated to the basement. A short duct from the top of the enclosure delivered the warm air by stack effect to a large grille in the middle of the floor of

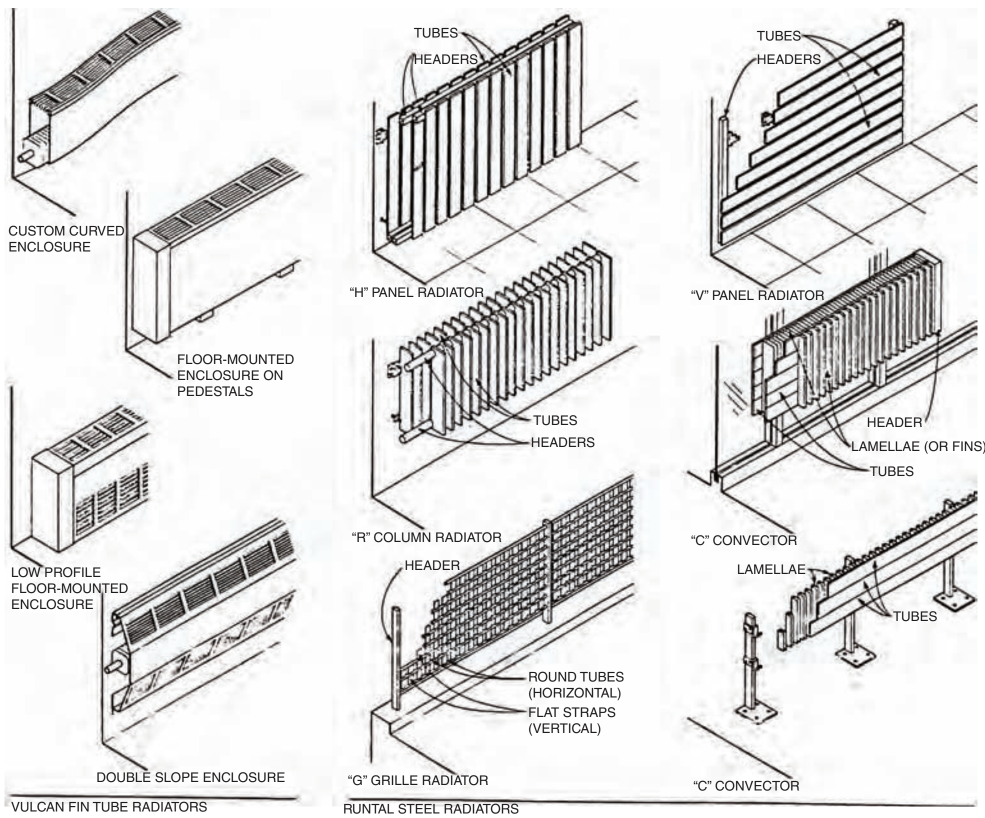
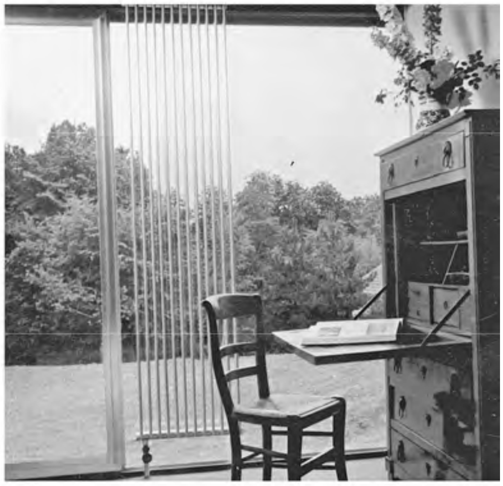


Fig. 12.79 *Hot water radiators are available in bright colors and are based on simple components. (Reprinted by permission from AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 10th ed.; © 2000 by John Wiley & Sons, Inc.)*



(a) (b)

Fig. 12.80 *Hot water radiators fit below a window (a) at the Mayer Art Center, Phillips Exeter Academy, Exeter, New Hampshire. Amsler Hagenah MacLean, Architects. (Photo by Alex Beatty.) (b) Radiator formed by flat tubes. (Courtesy of Runtal/North American Energy Systems.)*

the parlor. Other rooms, including those in upper stories, shared a little of this warmth when doors were left open. The system functioned much like a local system.

By the middle of the twentieth century, very gradual changes culminated in systems essentially like the ones illustrated in Figs. 12.19 and 12.81. The improvements included:

Automatic firing of oil or gas burners

Operational and safety controls

Air ducted to and from each room

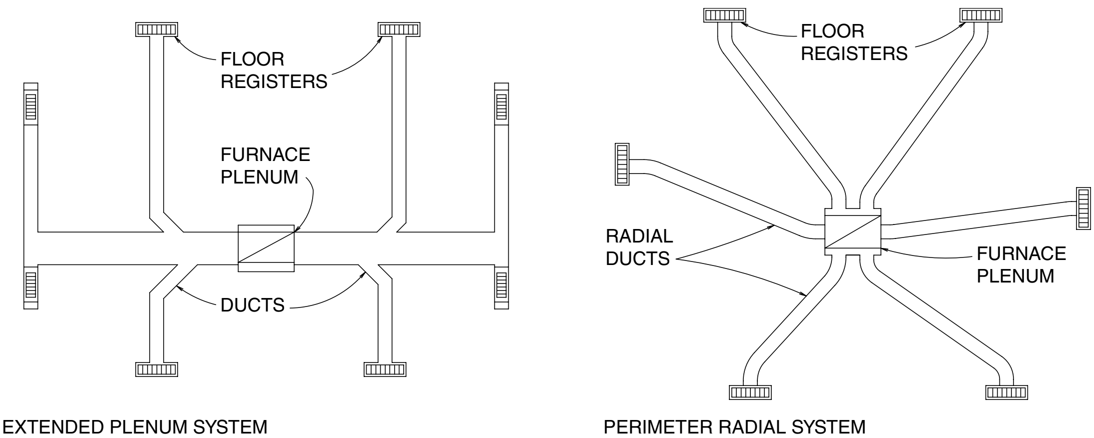


Fig. 12.81 *Typical duct distribution arrangements from residential furnaces. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *10th ed.; © 2000 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

Blowers to replace stack effect

Air filters

Adjustable delivery registers

By the 1960s, basements were beginning to disappear, and subslab perimeter systems became popular for basementless houses (Fig. 12.82). The heat source was located centrally and fully within the insulated envelope of the house; heat escaping from the unit merely helped heat the building. In general, air was delivered from below, upward across windows, to be taken back at a central high-return grille.

When electricity was used for space heating instead of oil and gas, provisions for combustion air, chimneys, and fuel storage were unnecessary. Horizontal electric furnaces began to appear in shallow attics or above furred ceilings. Air was delivered down from ceilings across windows and taken back through door grilles and open plenum space. Electric resistance furnaces use more electricity than heat pumps to provide the same heating capacity, so heat pumps have largely supplanted electric resistance furnaces (where climate permits).

As energy-efficient design gained strength, insulated windows and well-insulated roofs, walls, and floors lessened the need for space heating. From a central furnace or heat pump, short ducts could deliver warm air to the inner side of each room, because providing heat at well insulated windows was less essential. Air was returned to the furnace through grilles in doors and at the furnace or heat pump enclosure.

It is possible to clean both the recirculated air and the outdoor air by means of filters and (as appropriate) special air-cleaning equipment. Air may be circulated in nonheating seasons to reduce stuffiness. Outdoor air may be introduced to reduce odors and to make up for air exhausted by fans in kitchens, laundries, and bathrooms. Central cooling can be retrofit into an air system if ducts are designed to accommodate this; cooling often requires greater rates of air circulation than does heating. Humidification can be provided by a humidifier located in the air stream, and if cooling is included in the design, dehumidification can be accomplished in summer. For both heating and cooling, a common arrangement is to place supply registers in the floor, below areas of glass. This is important for winter operation. With adequate attention to supply register placement, return grilles can be located so as to minimize return air ductwork. High return grilles

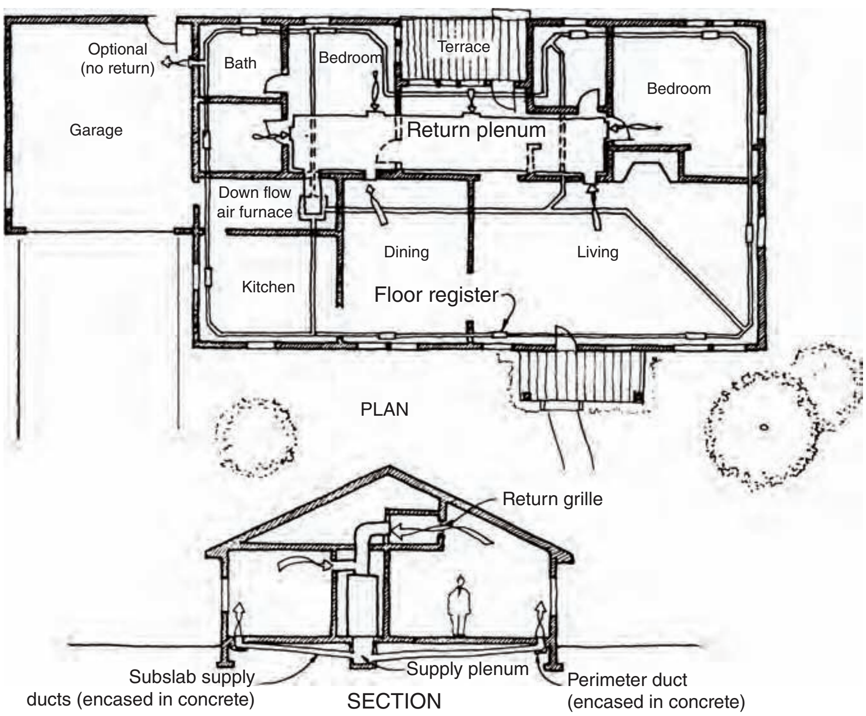


Fig. 12.82 *Forced-warm-air, perimeter loop system, adaptable for a cooling coil at the furnace. No return air is taken from the kitchen, baths, or garage.*

pick up warmer air for reheating at the equipment. In many systems, air circulates at all times and is warmed or cooled as required.

Figure 12.83 shows the relationship between a furnace, the duct distribution tree, and some elements of the spaces they serve. Ducts also can be lined with sound-absorbing material to mitigate noise transfer—but beware of lining materials that support mold and mildew growth. The following noise-reduction suggestions are recommended:

- Do not place the blower too close to a return grille.
- Select quiet motors and cushioned mountings.
- Do not permit connection or contact of conduits or water piping with the blower housing.
- Use a flexible connection between furnace and ductwork.

In the absence of project-specific criteria, duct sizes may be selected on the basis of permissible air velocity in the duct segment (or delivery device) of interest. Table 12.9 provides recommended maximum velocities related to achievement of acoustical design objectives. These velocities are not based upon optimizing system energy efficiency (which would generally lead to lower velocities).

EXAMPLE 12.5 The main duct in a low-velocity, warm air system for a residence delivers 1600 cfm (755 L/s). It is located above a drywall ceiling and has a rectangular cross section. Select a size for this duct.

SOLUTION

Table 12.9 indicates that for a residence, RC(N) should be between 25 and 35. Choose the quieter value of RC(N) = 25; 1700 fpm would then be the maximum acceptable velocity. The area of the duct in square inches would be

$$\frac{1600 \text{ cfm} \times 144 \text{ (in.}^2\text{/ft}^2\text{)}}{1700 \text{ fpm}} = 135 \text{ in.}^2$$

A 10 × 14 in. (140-in.^{2}) duct is acceptable; a larger duct would produce less noise and require less fan power to overcome friction. ■

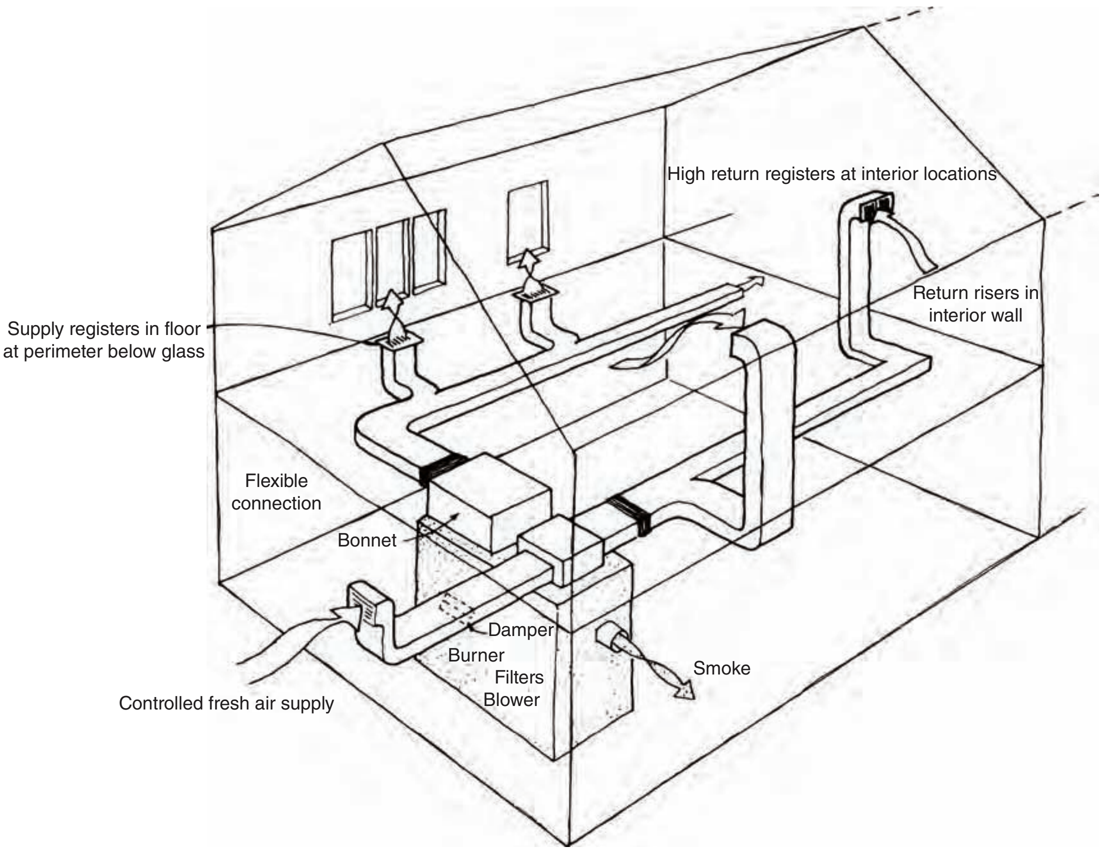


__Fig. 12.83__ Conventional warm-air furnace and ductwork. Low supply registers under windows and high return grilles at interior walls help ensure distribution within the spaces.

TABLE 12.9 Maximum Air Velocities for Ducts and Grilles (based upon noise criteria)

PART A. MAIN DUCTS[a]

		Maximum Airflow Velocity			
		fpm		m/s	
Duct Location	**Design RC(N)**	**Rectangular**	**Circular**	**Rectangular**	**Circular**
In shaft or above drywall ceiling	45	3500	5000	17.8	25.4
	35	2500	3500	12.7	17.8
	25	1700	2500	8.6	12.7
Above suspended acoustic ceiling	45	2500	4500	12.7	22.9
	35	1750	3000	8.9	15.2
	25	1200	2000	6.1	10.2
Duct within occupied space	45	2000	3900	10.2	19.8
	35	1450	2600	7.4	13.2
	25	950	1700	4.8	8.6

PART B. FACE VELOCITIES AT SUPPLY AND RETURN OPENINGS[b]

		Maximum Airflow Velocity	
Type of Opening	**Design RC(N)**	**fpm**	**m/s**
Supply air outlet	45	625	3.2
	40	560	2.8
	35	500	2.5
	30	425	2.2
	25	350	1.8
Return air opening	45	750	3.8
	40	675	3.4
	35	600	3.0
	30	500	2.5
	25	425	2.2

PART C. RANGES OF RC (N)[c]

Function	**HVAC System Noise in Unoccupied Spaces, RC(N)**
Residential, private	25–35
Hotels, individual rooms, meeting rooms	25–35
Lobbies, corridors, service areas	35–45
Office buildings, private offices, conference rooms	25–35
Teleconference rooms	25 (max.)
Open-plan offices	30–40
Lobbies, circulation	40–45
Hospitals and clinics, private rooms, operating rooms	25–35
Wards, corridors, public spaces	30–40
Performing arts, drama theaters, music teaching rooms	25 (max.)
Music practice rooms	35 (max.)
Churches, mosques, synagogues	25–35
Schools, lecture halls	35 (max.)
Classrooms over 750 ft^2 (70 m^2)	35 (max.)
Classrooms up to 750 ft^2 (70 m^2)	40 (max.)
Libraries	30–40
Laboratories (with fume hoods), group teaching	35–45
Research, telephone use, speech communication	40–50
Testing/research, minimal speech communication	45–55
Courtrooms, unamplified speech	25–35
Amplified speech	30–40
Sports indoors, school gymnasiums and pools	40–50
Large capacity, with amplified speech	45–55

Source: Reprinted with permission; ©ASHRAE, 2011 *ASHRAE Handbook—HVAC Applications*.

[a]Branch duct velocities should be about 80% of those listed, whereas velocities in final runouts to outlets should be 50% or less. Elbows and other fittings can increase noise substantially, so airflows should be reduced accordingly.

[b]These are "free" opening velocities. Diffusers and grilles can increase sound levels, in which case these velocities should be reduced accordingly.

[c]See also Table 23.8 for recommended NC levels.

Figure 12.84 illustrates a device that simplifies duct sizing. At a glance, it shows many duct cross-sectional configurations that will satisfy the combined requirements of friction, airflow, and air velocity.

Dampers and other accessories are necessary to balance an air system and adjust it to the desires of the occupants (Fig. 12.85). Splitter dampers are used where branch ducts leave the larger trunk ducts. The flow of each riser can be controlled by an adjustable damper in the basement at the foot of the riser. Labels should indicate the rooms served. Some codes require dampers of fire-resistant material actuated by fusible links to prevent the possible spread of fire through a duct system. Figure 12.85*d* shows how turning vanes can be used to improve airflow at sharp turns. Turning vanes reduce friction within the ductwork, thus reducing the total static head (Fig. 12.86) against which the supply fan must work.

Supply registers (Fig. 12.87) should be equipped with dampers, and their vanes should be

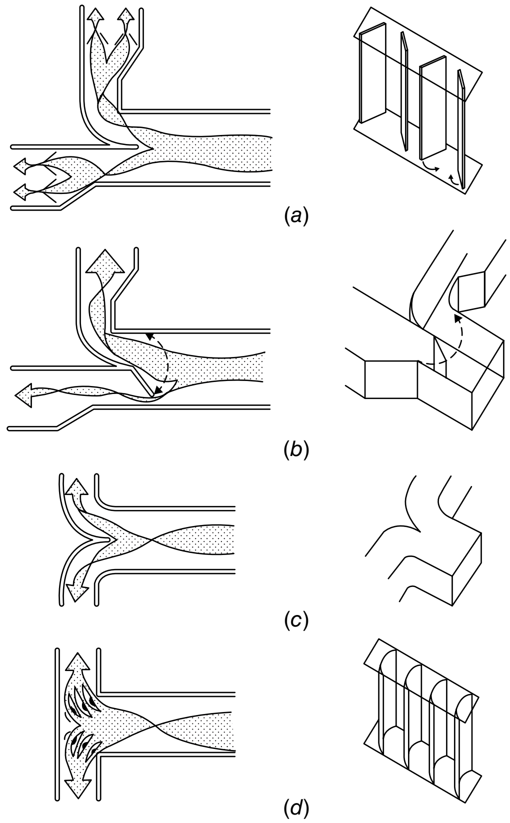


Fig. 12.85 *Air controls in ducts. (a) Air adjustment by opposed-blade dampers. (b) Air adjustment by a splitter damper. (c) Conventional turns in ducts. (d) Right-angle turns with turning vanes—a more compact method.*

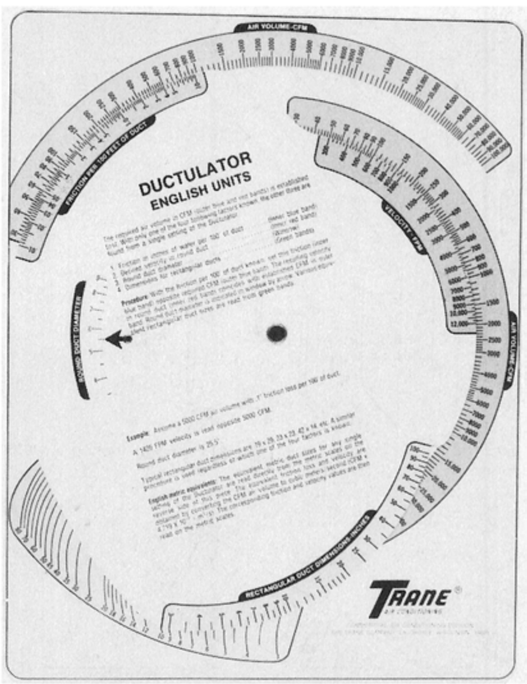


Fig. 12.84 *The Ductulator duct-sizing device is available from the Trane Company. The designer selects any two factors (e.g., friction and airflow volume), and the device displays all other factors (e.g., air velocity, required diameter of a round duct, or combinations of equivalent rectangular-duct cross sections).*

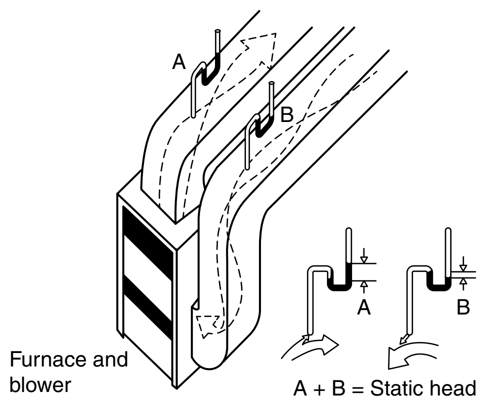
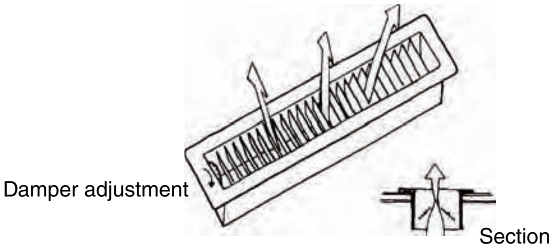
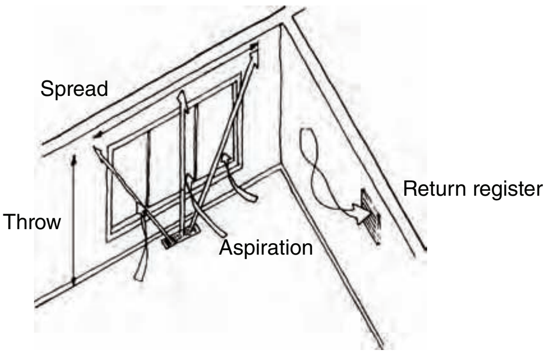


Fig. 12.86 *The static head is the pressure, measured in inches of water (or pascals), required to overcome friction loss in an air distribution system.*



(*a*)



(*b*)

Fig. 12.87 *The typical floor register (a) is 2¼ in. × 12 in. (60 mm × 300 mm). It has diverting vanes for spread and an adjustable damper. See Table 12.10 for characteristics. (b) Spread and throw; cooler room air is induced by aspiration to join the stream of warm air, resulting in a pleasant air stream that crosses the room.*

arranged to disperse the air and to reduce its velocity as it enters a room. This is commonly done by providing vanes that divert the air, half to the right and half to the left. When a supply register is placed in the corner of a room, the vanes should deflect all the air away from the corner. Return grilles are usually of the slotted type in walls and of the grid type in floors. All registers and grilles should be made tight at the duct connection. See Tables 12.9 and 12.10 for selection of registers based upon output and recommended face velocity.

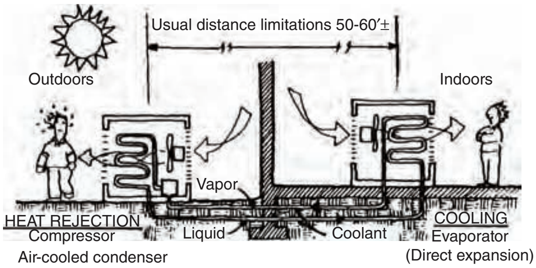
Cooling coils in furnaces: Active cooling is a much more recent development than heating; in its early days, cooling was generally adopted as a retrofit to existing heating systems. Adding a cooling coil to a warm air furnace provided air conditioning (as opposed to heating). This conceptual approach to residential air conditioning persists. Figure 12.88 shows a schematic diagram of an air-to-air, direct expansion refrigeration system and how this can be coupled to a typical furnace. Figure 12.89 shows another popular arrangement in which airflow through the furnace and coils is horizontal.

Hydronic perimeter and air: This system combines a perimeter hot water heating pipe with an overhead air-handling system. A boiler with a tankless coil provides domestic hot water and also supplies a perimeter loop and a coil in an air-handling

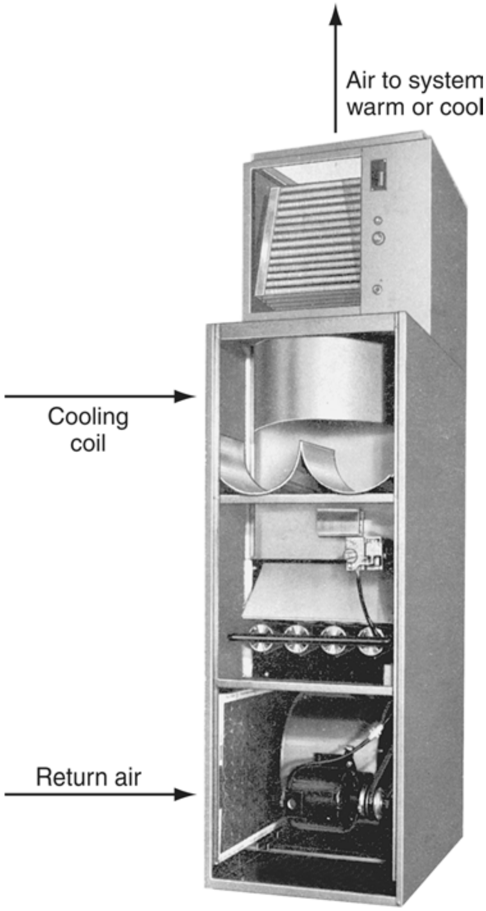
TABLE 12.10 Typical Residential Forced-Air Register, 2¼ × 12 in. (60 × 300 mm)

PART A. I-P UNITS								
Heating (Btu/h)	3045	4565	6090	7610	9515	11,415	13,320	15,220
Cooling (Btu/h)	855	1280	1710	2135	2670	3200	3735	4270
cfm	40	60	80	100	125	150	175	200
Vertical throw (ft)	3	4	5	6	8	10	12	14
Vertical spread (ft)	6	8	10	11	14	17	22	25
Face velocity (fpm)	280	420	565	705	880	1050	1230	1400
PART B. SI UNITS								
Heating (W)	890	1340	1780	2230	2790	3340	3900	4460
Cooling (W)	250	375	500	625	780	940	1090	1250
L/s	19	28	38	48	59	71	83	95
Vertical throw (m)	0.9	1.2	1.5	1.8	2.4	3.0	3.7	4.3
Vertical spread (m)	1.8	2.4	3.0	3.4	4.3	5.2	6.7	7.6
Face velocity (m/s)	1.4	2.1	2.9	3.6	4.5	5.3	6.2	7.1

Source: Lima Register Company.
SI conversions added by the authors.



(*a*)



(*b*)

Fig. 12.88 *The compressive refrigeration cycle (a) with an exterior air-cooled heat rejection unit and an interior cooling coil suitable for placement in a central air handler. (b) Cooling/heating residential air-handling unit. Cutaway view shows an upflow air pattern. At the lower left is the return air intake and a filter; adjacent are the fan and motor. Above these components are the gas-burning elements. At the top is the direct-expansion cooling coil. (Courtesy of American Furnace Division, Singer Company.)*

unit supplying a ductwork system. The total heating load is met by a combination of radiant heat generated by the perimeter loop and heated air from the overhead air distribution system.

As installed in the Levittown standardized houses, the perimeter loop consists of ½- or ¾-in. (13- or 19-mm) tubing embedded 4 in. (100 mm) below the top of the floor slab to overcome the cold slab effect. It has the capacity to maintain a 35F° (19C°) differential between the inside and outside temperatures at the perimeter.

The air-handling unit and overhead duct system, incorporating supply outlets in each room and a central return, is used throughout the year. Its cooling coil is connected to an adjacent outdoor condensing unit (Fig. 12.90). Because the heating load is shared by the slab loop and by the warm air system, winter indoor temperature remains rather constant. The air can be distributed at roughly 120°F (49°C), which is 20F° (11C°) less than with a conventionally ducted system.

(c) Evaporative Cooling Systems

Evaporative cooling systems are applicable (under the right climate and functional conditions) to both small and large buildings. Several of these systems are presented here. A few of these systems are hybrid (requiring some operational assistance from mechanical/electrical equipment); evaporative coolers (both direct and indirect) are best classified as active systems.

Evaporative cooling—misting: The net effect of evaporative cooling is no total change in the heat content (enthalpy) of the treated air; DB temperature is lowered, but there is an increase in RH. One of the most direct approaches to evaporative cooling is a misting or fogging system whereby a fine spray of water droplets is blown into the air. A common application is for small outdoor areas—the team benches at football stadiums, refreshment pavilions, outdoor seating at a restaurant. Large spaces in hot, dry climates can also benefit; Fig. 12.91 shows mist descending from a diffuser in Phoenix, Arizona. A large space using fogging (in a Michigan conservatory) is shown in Fig. 12.55.

Evaporative cooling—roof spray: In the past, when roofs were poorly insulated, roof sprays were a rather common way to reduce heat gains.

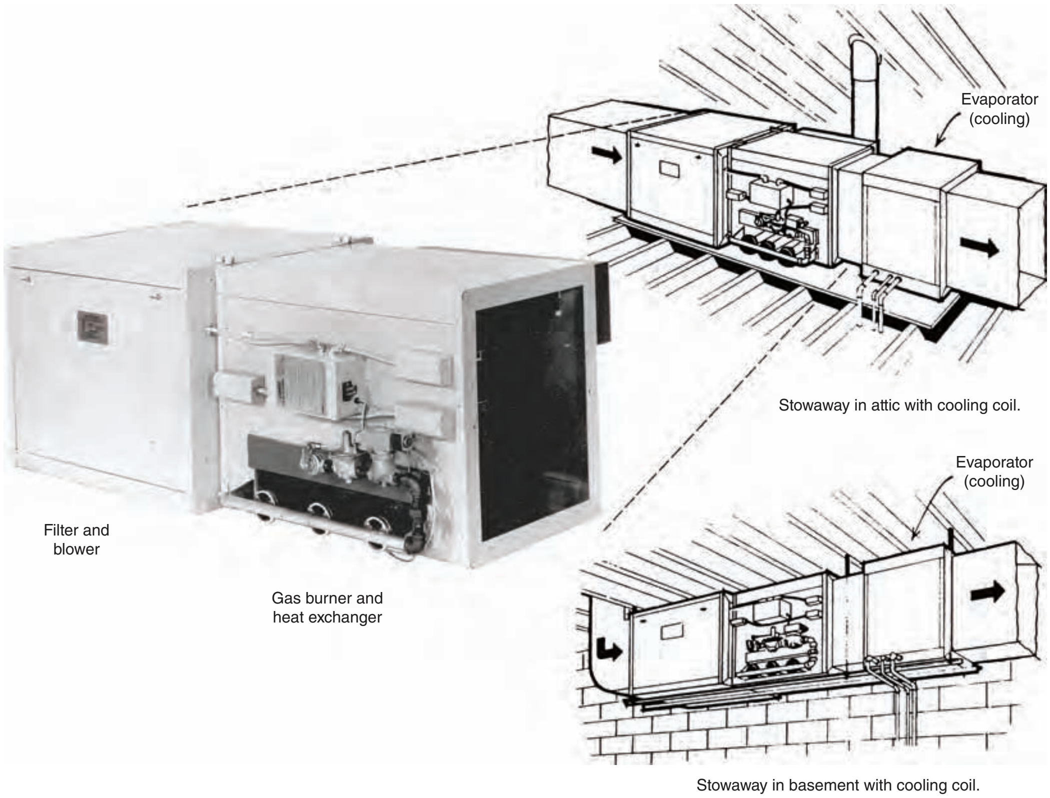


Fig. 12.89 *Compact horizontal flow combinations for forced-air heating and cooling. The small pipe between the two refrigerant pipes of the cooling unit is a water drain that carries away the condensed moisture removed from the air. The heating unit requires gas and flue/exhaust. Refrigerant pipes connect to the outdoor compressor–condenser unit.*

New variations on this approach promise potential energy savings.

Roof color is the first design consideration. White or near-white roofs are the first step toward energy savings through control of sol-air temperature. Emissivity is also involved; the higher the emissivity, the more readily a roof surface reradiates its heat to the sky. Table 12.11 compares the solar absorptance, albedo (overall solar reflectance), and emittance of some common roofing materials. A combination of high albedo and high emittance resists solar heat gain most effectively. This combination can also reduce heat island effect in urban areas. The concept of solar reflectance index (SRI) was developed to allow quick comparisons between roofing products. The SRI scale ranges from 0 (approximately 5% albedo and 90% emittance; roughly equal to black asphalt shingles) to 100 at 80% albedo and 90% emittance (in the ballpark with T-EPDM).

An approach called the *night roof spray thermal storage system* (NRSTS) cools water on a roof at night, using both night sky radiation and evaporation. The water is then stored for use the next day in building cooling. The water can be stored either on the roof (below floating insulation, above a structural ceiling) or in a tank below the roof. When stored on the roof, it becomes a variant of the roof pond cooling system. When stored in a tank, the water can be circulated through a cooling coil to precool air before the air is further cooled by chilled water provided by a chiller. Three variations are shown in Fig. 12.92.

At a Nogales, Arizona, border patrol station, a 6500-ft^2 (604-m^2) flat white roof was retrofitted with an NRSTS, utilizing a 10,000-gal (37,850-L)

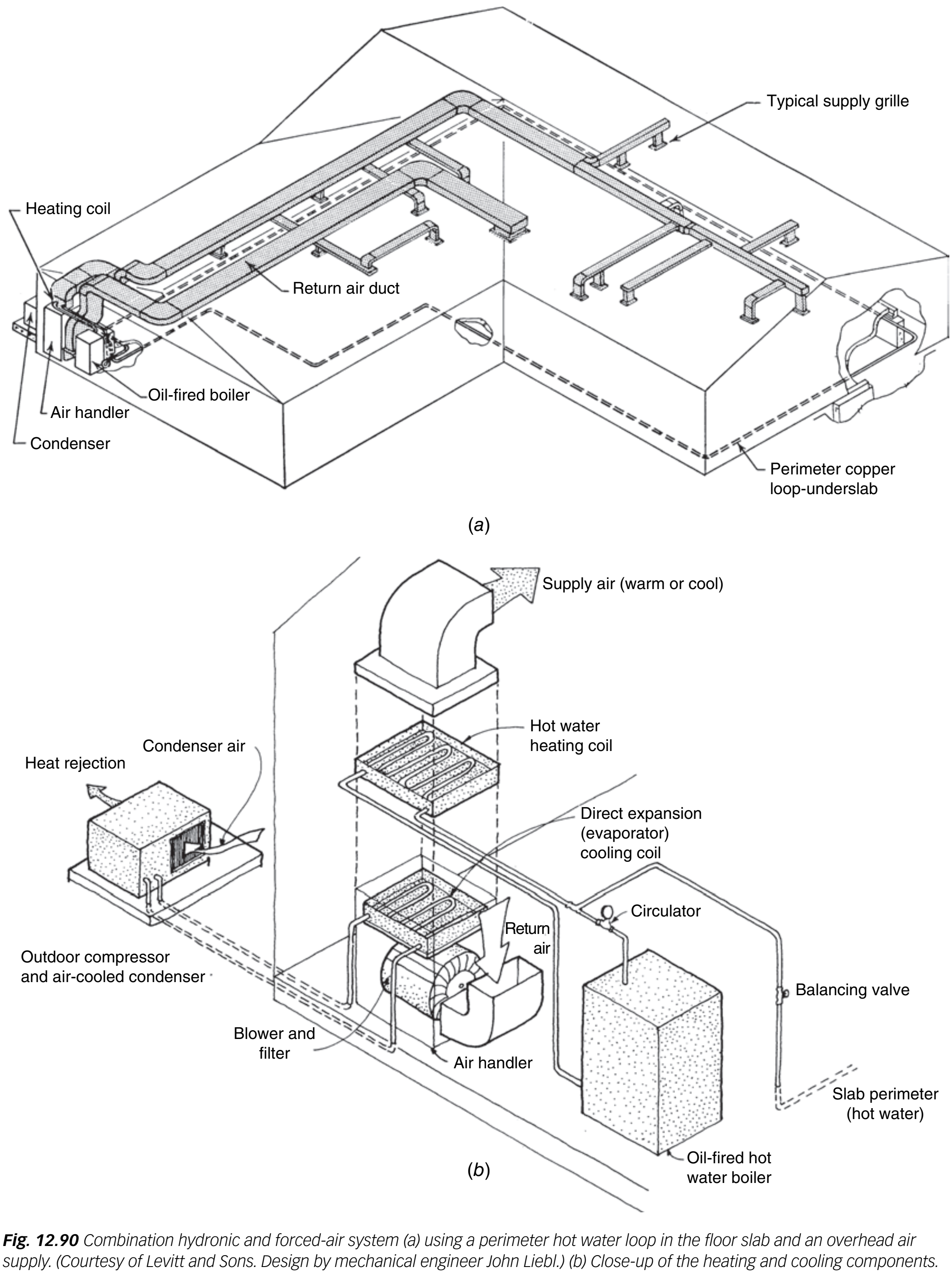


Fig. 12.90 *Combination hydronic and forced-air system (a) using a perimeter hot water loop in the floor slab and an overhead air supply. (Courtesy of Levitt and Sons. Design by mechanical engineer John Liebl.) (b) Close-up of the heating and cooling components. The boiler heats both the slab perimeter and the coils in the air stream.*

(a) (b)

Fig. 12.91 *(a), (b) Mist is sprayed from a diffusing system in a building located in Phoenix, Arizona. It provides psychological reinforcement of the evaporative cooling effect during a hot, dry summer. (© Alison Kwok; all rights reserved.)*

aboveground tank. Over the summer of 1997, it averaged a cooling capacity of 250 Btu/ft^2 per day. Water use at various sites has averaged 4 to 5 gal/h (15 to 19 L/h) per 1000 ft^2 (per 93 m^2) of roof area. Details are presented in Bourne and Hoeschele (1998). A similar system was employed at the award-winning building housing the Department of Global Ecology at Stanford University.

TABLE 12.11 Solar Performance of Roofing Materials

Material	Absorptance (%)	Albedo (%)	Emittance (%)
White asphalt shingles	79	21	91
Black asphalt shingles	95	5	91
White granular-surface bitumen	74	26	92
Red clay tile	67	33	90
Red concrete tile	82	18	91
Unpainted concrete tile	75	25	90
White concrete tile	27	73	90
Galvanized steel (unpainted)	39	61	4
Aluminum	39	61	25
Siliconized white polyester over metal	41	59	85
Kynar white over metal	33	67	85
Gray EPDM	77	23	87
White EPDM	31	69	87
T-EPDM	19	81	92
Hypalon	24	76	91

Source: Lawrence Berkeley National Laboratory.

Evaporative coolers: These devices are a move toward mechanical implementations of evaporative cooling (as opposed to the fundamentally architectural approaches described previously). Evaporative coolers (Fig. 12.93) are also affectionately termed *swamp coolers* and *desert coolers* and are familiar devices in hot, arid climates. They are also used in other climates for special high-heat applications such as restaurant kitchens. They require a small amount of electricity to run a fan and an input of water. The psychrometric process of evaporative cooling is explained in Section 12.4(d).

The typical evaporative cooler (as in Fig. 12.93) needs full access to outdoor air and is thus often set on a roof, although through-the-wall units are also available. Large quantities of dry, hot outdoor air are blown through pads kept moist by recirculating and makeup water. The "cooled" air is delivered to the indoor space(s). In addition to the sensible cooling produced by the process itself, additional cooling effect is often provided by the impact of air motion on bodily heat loss.

Air introduced into the indoor space must be exhausted in order for the system to operate properly. By skillfully selecting the room through which the air is exhausted, a designer can route cool air as desired along any chosen path from unit to relief opening. The closer to the inlet, the cooler the air; the closer to the exhaust, the warmer the air.

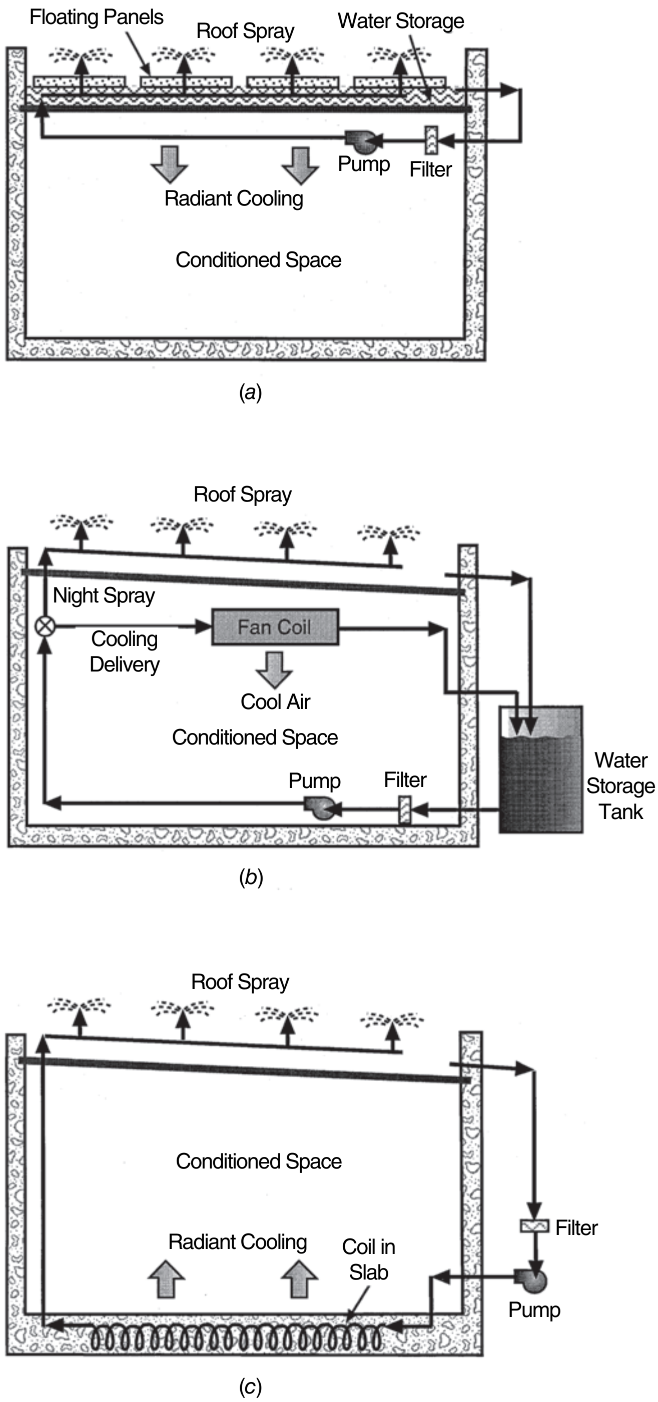


Fig. 12.92 *Night roof spray thermal storage systems (NRSTS). (a) This version approximates the performance of the roof pond. (b) Remote water storage allows use of the cooled water at any time. (c) The floor slab is used as thermal storage in this version. (From* Technical Installation Review, *December 1997: WhiteCap Roof Spray Cooling System. Federal Energy Management Program, U.S. Department of Energy.)*

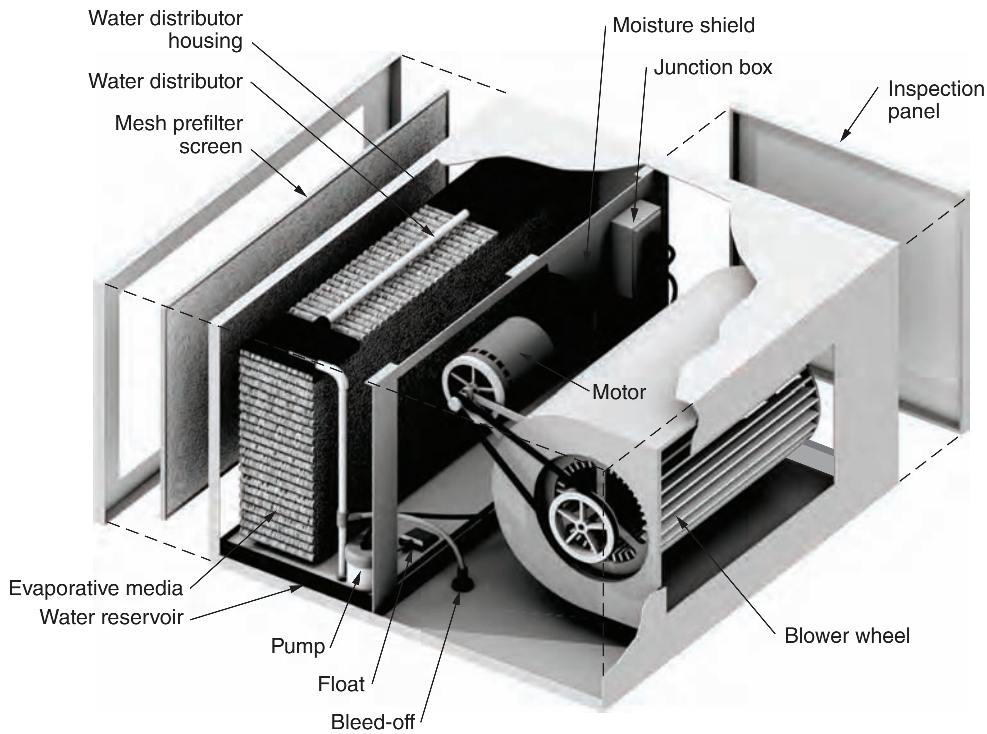


Fig. 12.93 *The UltraCool evaporative cooler has a low profile and uses internal components of plastic or stainless steel to reduce corrosion. Typical dimensions for a 4000-cfm (1890-L/s) unit are 35 in. H × 42 in. W × 48 in. D (890 × 1070 × 1220 mm). (Courtesy of Champion Cooler Corporation, El Paso, TX.)*

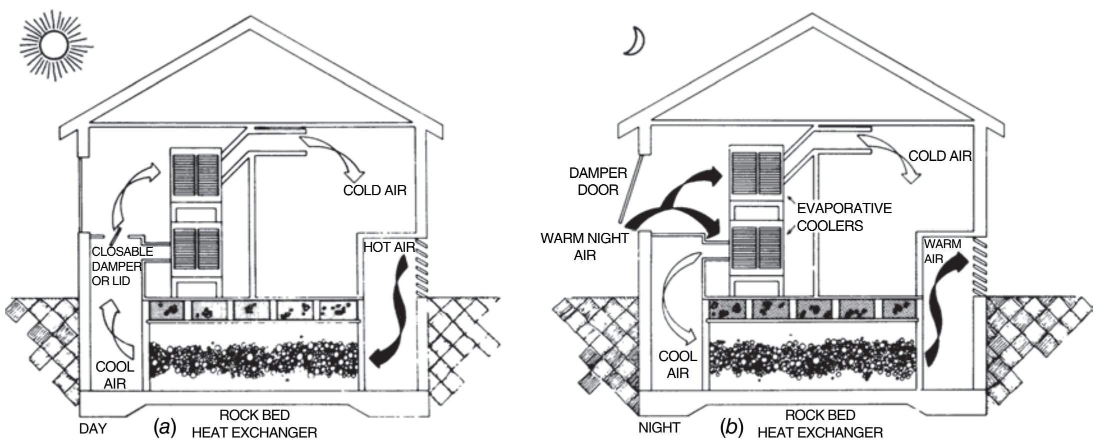


Fig. 12.94 *(a, b) Direct–indirect evaporative cooling utilizing a rock bed for storage and heat exchange. (Reprinted by permission of the Environmental Research Laboratory, University of Arizona.)*

Indirect evaporative cooling: The preceding discussion relates to direct evaporative cooling (wherein processed outdoor air is directly introduced to a space). Unfortunately, some areas have such hot and/or humid summer daytime conditions that a direct evaporative approach cannot produce thermally comfortable indoor conditions. An indirect process can produce better indoor comfort conditions. A psychrometric process diagram illustrating this is shown in Fig. 5.16.

One of several possible variations is shown in Figs. 12.94 and 12.95. Warm, rather dry night outdoor air is evaporatively cooled and fed through a rock bed. The air temperature is low enough to cool the rock bed, and its RH is moderate. At the same time, the house is cooled by a second direct evaporative cooling unit. Figure 12.95 traces the process by day. Extremely hot, dry outdoor air (A) is drawn into the rock bed, where it is cooled by contact (D). It can then be passed through an evaporative cooler to achieve a better combination of RH and DB temperature (E). After picking up both sensible and latent heat, the air is exhausted (at approximately temperature F). Note that at condition F, it is still much cooler than outdoor air.

By comparison, simple direct evaporative cooling by day would have produced indoor supply air too hot and humid for comfort (B). Again, upon exhaust (C), it is still cooler than outdoor air.

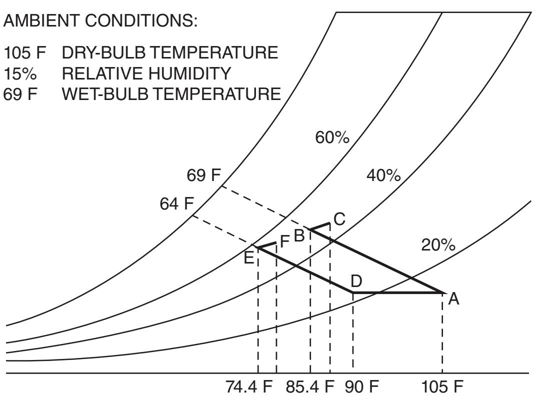
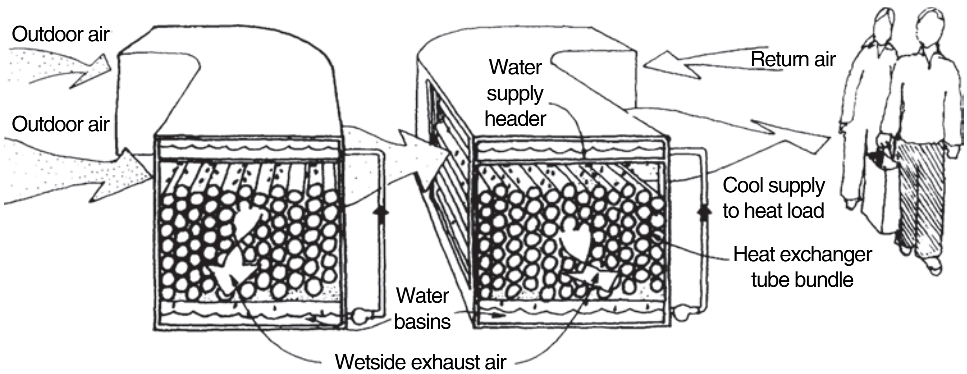


Fig. 12.95 *Comparing direct (A to B to C) and indirect evaporative cooling (A to D to E to F) on the psychrometric chart.*

Indirect evaporative cooling is combined with a direct refrigerant system in an innovative tent structure over a department store in the San Francisco Bay area (Fig. 12.96). Two layers of fiberglass, Teflon-coated fabric, separated by an average of 12 in. (300 mm), are supported by a network of cables hung from eight masts. The tent roof covers about 70,000 ft^2 (6500 m^2) of sales floor; its 7% translucency to sunlight provides 450 to 550 footcandles (4800–5900 lux) of daylight. This greatly reduces the need for electric lighting, although some electric lamps, clipped onto exposed fire sprinkler pipes, are used as accent lighting. About 3.5 W/ft^2 (37.7 W/m^2) of solar gain, mostly in the form of diffused daylight, penetrates the tent cover. When this solar gain is combined with heat gains from people and electric accent lighting, a cooling load is always generated (even in San Francisco Bay's mild climate, which rarely falls below 45°F [7°C]). The roof's relatively high U-factor is thus advantageous in helping the building lose heat. Because the San Francisco area overheats even more rarely, such low resistance to heat flow is not seriously disadvantageous in summer.

To remove the heat gain, four sets of direct refrigerant equipment are provided at the tent perimeter on grade. These feed into a perimeter plenum, from which the entire store is supplied with cool air. The exhaust air is collected at the center and returned to help with cooling. Indirect evaporative cooling (also called sensible evaporative refrigeration) units are used to cool air (see Fig. 12.96*b*). In this application, two units work in tandem. Air to be cooled (supply air) enters the heat exchanger of the first unit, which is cooled by evaporative cooling of outdoor air. During peak temperature periods, the supply air is only somewhat cooled by this process; sufficiently low temperatures for use in the interior are obtained by passing the air through the second unit's heat exchanger. This second unit is cooled by evaporative cooling of the *exhaust* air from the store, which is cooler than outdoor air under summer conditions. Thus, the exhaust air does some useful work before exiting. This two-stage, indirect evaporative cooling process allows the supply air to be cooled without raising the RH. This would not be the case if direct evaporative cooling were used.

(*a*)



(*b*)

Fig. 12.96 *Bullock's Department Store, San Mateo, California. (a) The eight-masted white fabric roof, highly reflective to ward off solar radiation, transmits about 7% of daylight to provide ample diffuse daylight for sales areas. (Photo by Steve Proehl. Environmental Planning and Research, Inc., architects; Giampolo and Associates, Inc., mechanical and electrical engineers.) (b) Cooling is provided by a two-stage, indirect evaporative cooling system, which uses much less energy than does conventional vapor compression refrigeration.*

12.18 HVAC SYSTEMS FOR LARGE BUILDINGS

Large buildings typically have so many thermal zones, and there are so many ways to move heat/coolth from one place to another and to introduce heat/coolth into a space, that literally hundreds of HVAC system variations have been devised over the years. Several of the more typical systems are introduced in this section. Figure 12.97 provides a schematic representation of a range of HVAC system approaches—which, as they increase in complexity and flexibility, include increasing numbers of heat-transfer loops.

Direct refrigerant (DX) systems are typically used in smaller-scale buildings, but are also applicable to some larger building situations. Big box retail stores, for example, typically use large rooftop packaged air-conditioning units. These are essentially local systems—each serving a section of the store floor area (even though the store is open-plan). DX systems were discussed in Section 12.8(a).

Large-building HVAC systems in general tend to be central systems. As noted under taxonomy (Section 12.15), central HVAC systems fall into three broad categories based upon the distribution medium chosen: (1) all-air systems; (2) air–water systems; and (3) all-water systems. Common implementations of these systems will be presented.

(a) All-Air Systems

Several variations of all-air systems are either commonly used in current building designs or are of historical interest. Because air is the only heat-transfer medium connecting a central mechanical room (air-handing unit) and the zones it serves, and because air holds much less heat per unit volume than water, the distribution trees (ductwork) for this group of systems can be rather large. All-air systems are very often the HVAC system type of choice because they can produce comfortable results while effectively regulating IAQ, temperature, and humidity at reasonable first cost and with acceptable energy efficiency (for most systems).

A signature aspect of an all-air system is ductwork—often lots of ductwork—lots of large ductwork. Preplanning and coordination are important, to avoid conflicts and undesirable compromises during construction. Sometimes, to reduce duct sizes, high supply air velocities are used. High velocity generates more airflow noise and results in higher friction losses (resulting in higher energy use by fans)—high velocity air distribution should be used only sparingly, where space limitations are real and extreme.

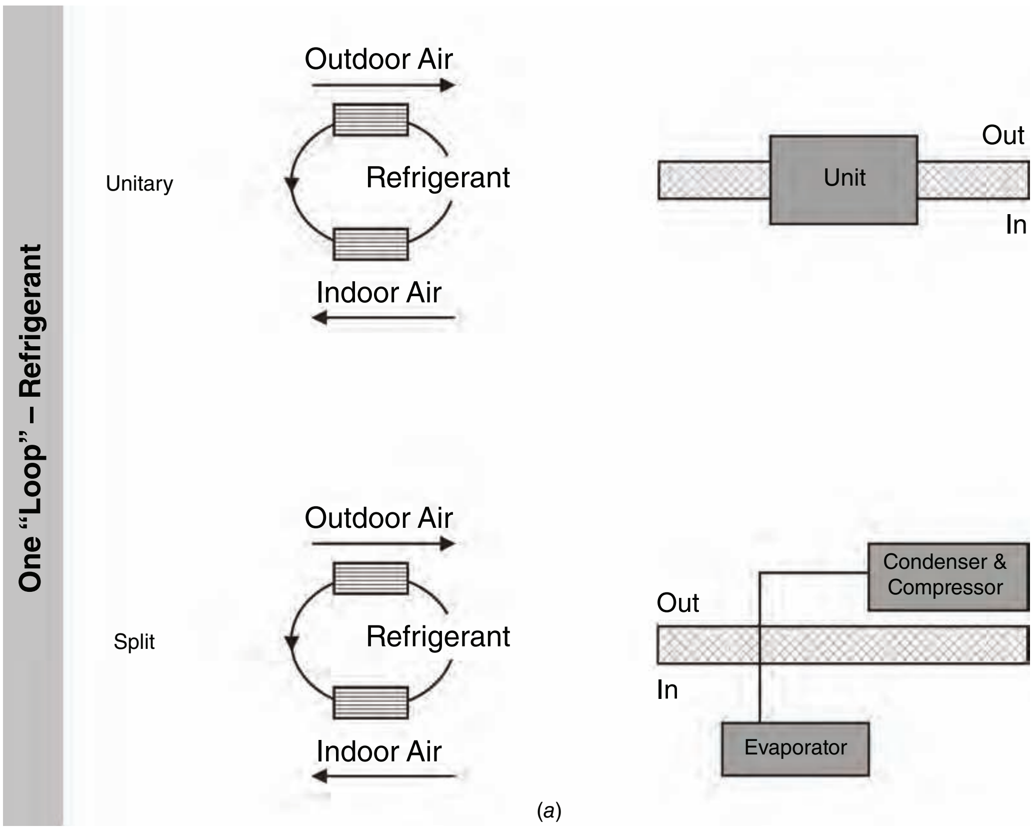
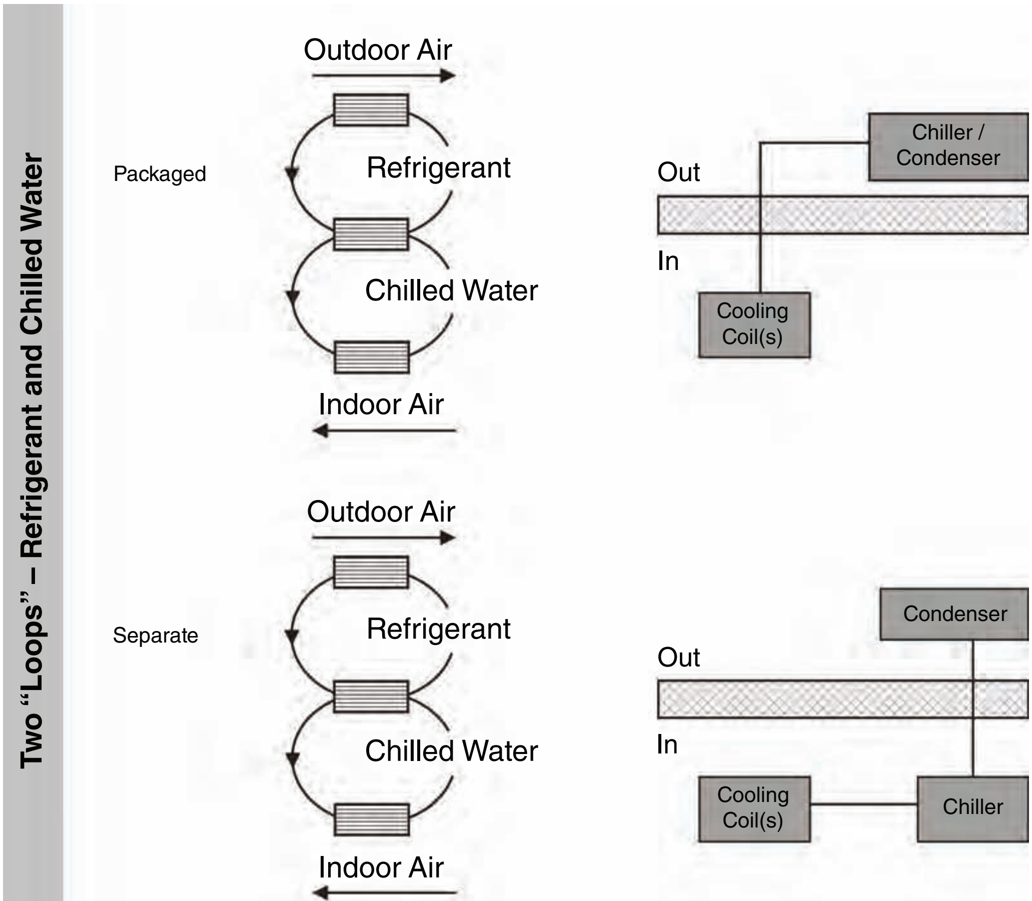
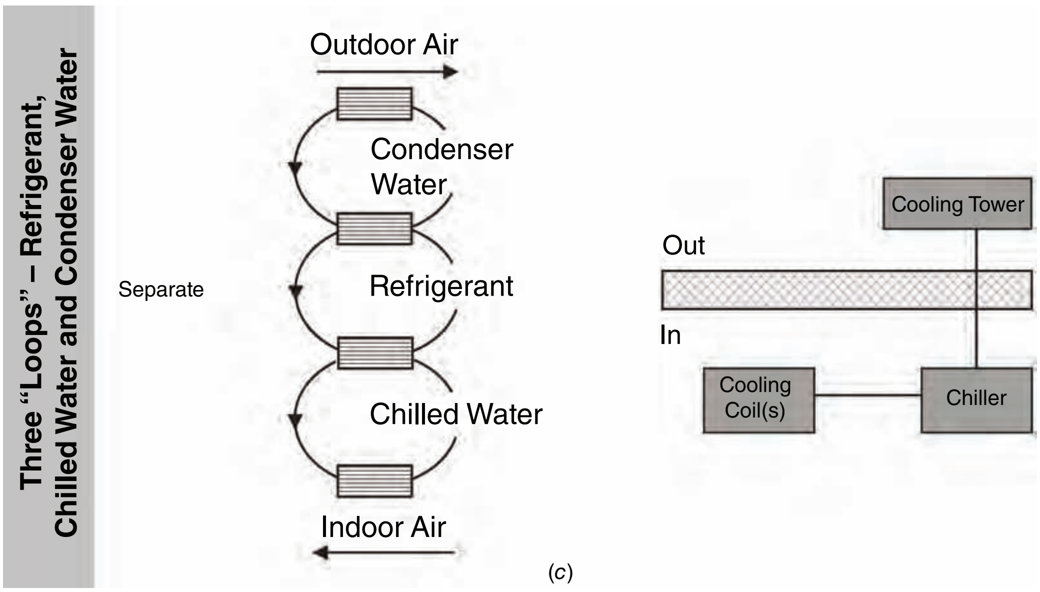


Fig. 12.97 (a), (b), (c) Schematic representations of HVAC heat-transfer loops; the simplest are the least architecturally flexible; the more complex are very flexible. (Redrawn by Karen Tse; © Walter Grondzik; all rights reserved.)



(b)



(c)

Fig. 12.97 *(Continued)*

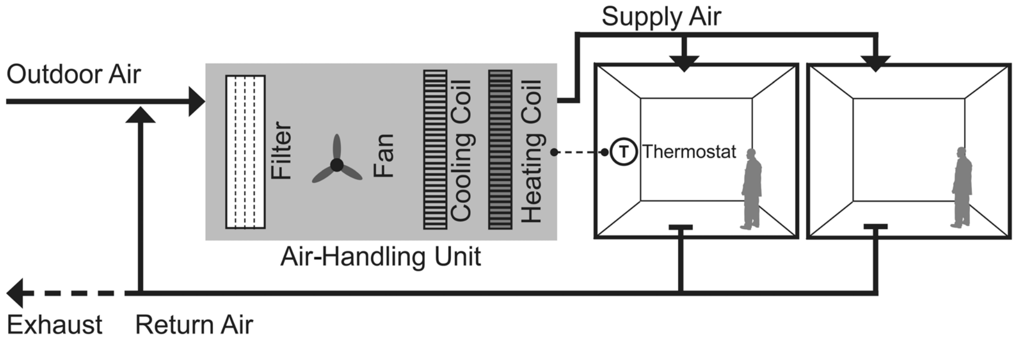


Fig. 12.98 *Schematic diagram of a single-zone all-air HVAC system. Components are representative of a typical system installation. Additional components (such as a preheat coil or humidifier) may be required for some projects/climates. Various heat and coolth sources (such as a DX or chilled water cooling coil, hot water or electric heating coil) may be used as appropriate. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

An all-air system allows for manipulation of pressure relationships throughout a building: negative pressures can be established in odorous or excessively humid locations (kitchens, bathrooms, pet shops, janitor closets, etc.), positive pressures in normal occupancy spaces. Pressure differences can be used to set up directional airflow patterns that help prevent the spread of contaminated air and can help manage smoke during a fire event (see Chapter 25). Indoor air quality control should not be a problem with an all-air system—although ensuring delivery of adequate outdoor air to all zones and under part-load operating conditions may require some creative thought.

Single-zone all-air system: This (Fig. 12.98) is a constant-volume system controlled by a single thermostat (thus, the single zone). In a constant volume system, air is delivered at the design airflow rate whenever the air-handling unit is in operation. A single supply duct leaves the AHU; it will divide into branches as necessary to deliver air to diffusers located in the zone. Temperature control (in response to changing loads) is accomplished by control of a modulating valve on the heating and/or cooling coils. The system can provide heating or cooling. Single-zone applications are surprisingly common across a range of building scales. A single-family residence is typically designed as a single thermal zone. A large warehouse might require 30 air-handling units, with each unit acting independently as a single-zone system. A high-rise building may require several zones per floor, but the majority of the floor area might be an open-plan office that acts as a single zone. The zone capabilities of a system do not need to apply to an entire building, but only to the portion of a building being served by a particular air-handling unit. Because thermal control is exercised at the AHU (versus near the occupied space) this system is not very flexible with respect to adaptation to space use changes over time.

Single-zone terminal reheat all-air system: This (Fig. 12.99) is a constant-volume, single-duct system controlled by multiple thermostats. The thermostats control reheat coils located near the various system zones. As many zones as necessary may be installed (limited only by space constraints). No heating coil is required in the AHU (since air for each zone passes through a heating coil). Heating may be provided for one zone at the same time that another zone is being cooled. The system is termed a reheat system because all the air supplied by the air-handling unit is cooled to a lowest common denominator temperature that will handle the load in the "worst" zone. Air supplied to any zone with "less-than-worst" loads is heated by the reheat coil (Fig. 12.100). If this approach sounds energy-wasteful, it is. Constant-volume terminal reheat systems are prohibited by most energy codes. The system is shown here because of its historical significance (they were once very common) and because the reheat approach will show up with a different system type (VAV). If it weren't for the energy waste, this would be a very popular and effective system—providing for acceptable IAQ, with good temperature and humidity control, flexible and adaptable

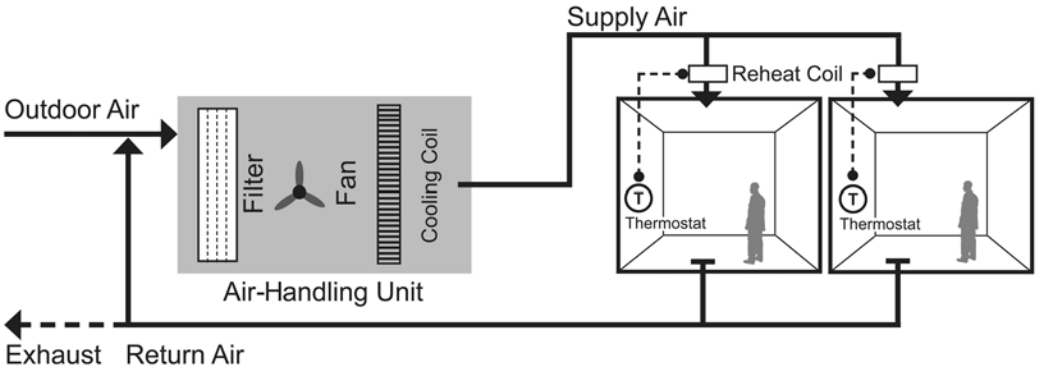


Fig. 12.99 *Schematic diagram of a single-zone terminal reheat all-air HVAC system. Components are representative of a typical system installation. Various heat sources (such as a hot water or electric heating coil) may be used, as appropriate. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

(zones can be easily added or removed), and with reasonable first cost. Several other all-air HVAC system types are in essence attempts to replicate the good points of a terminal reheat system while avoiding the energy waste.

Multizone all-air system: This system (Fig. 12.101) mixes hot and cold air streams to provide appropriate-temperature supply air for each of several zones. Zone control is exercised at the air-handling unit (through the operation of mixing dampers). Once air has been mixed to meet zone loads, it must be conveyed to the zone separately (without further mixing with air for other zones). Thus, a separate supply air duct must run from the AHU to each zone. Because of the multiple supply ducts, such systems will rarely exceed ten zones per air-handling unit. Even with that (physically imposed) limit, total distribution tree volume can grow to astonishing size. Careful spatial coordination is a must. A single return air stream collects air from all zones (this is the case for all the all-air systems). Use of a “bypass” deck, allowing return air to provide tempering effect (instead of heated air) can improve energy efficiency. Leakage between zones at the decks of hot and cold coils is common, however, which decreases energy efficiency. This

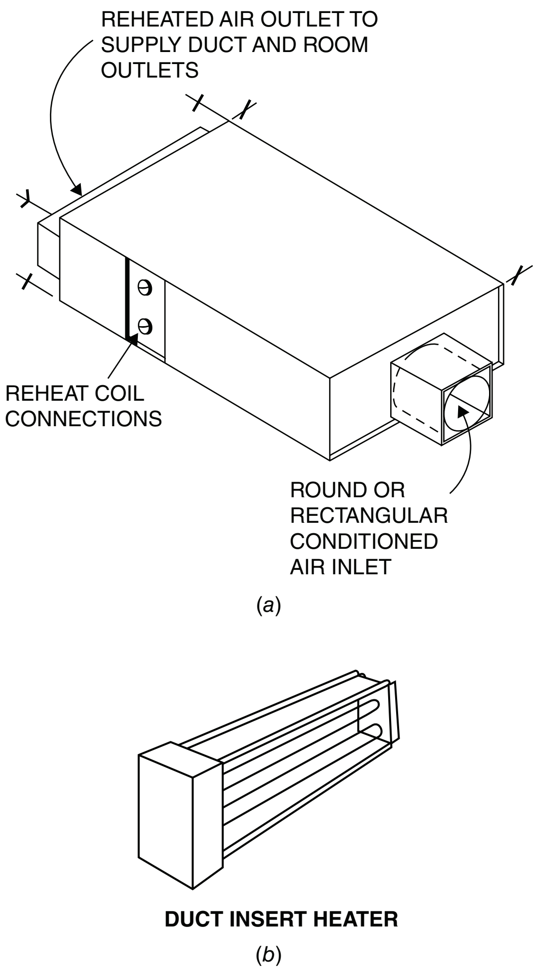


Fig. 12.100 *Reheat system terminal-control options. (a) A terminal box where velocity and pressure are reduced while air is heated. (b) Electric heating coil designed for insertion within a duct. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *9th ed.; © 1994 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

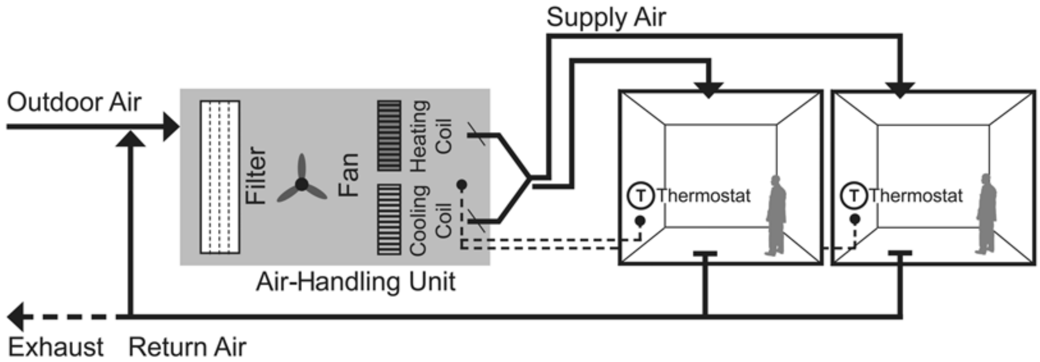


Fig. 12.101 *Schematic diagram of a multizone all-air HVAC system. Components are representative of a typical system installation. Note that each zone requires a separate supply air duct. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

type of system is likely to be used in medium-sized buildings (or portions of buildings) where there is no expectation of flexibility for future zoning changes. Adding or deleting a zone requires replacing the supply air ducts. The system name is multizone (not "multiple zone").

Dual-duct all-air system: This system (Fig. 12.102) is conceptually similar to a multizone system in terms of control approach. Two air streams ("hot" and "cold") are mixed under control of a zone thermostat in order to produce supply air that will meet the cooling/heating needs of the zone. The air streams, however, are mixed not at the AHU but in a mixing box located near each zone. There is no limit to the number of zones provided, changes in zoning are easily made without system-wide disruption, and the system is reasonably energy efficient. Two supply ducts run throughout the building—impacting system first cost and spatial coordination difficulty. This is a constant-volume system. Dual-duct systems are rarely selected now, except where the pressure control benefits of a constant-volume system are compelling. The building volume required to route the system's three (two supply, one return) full-sized air distribution trees is hard to justify, given that a VAV system can provide acceptable comfort for most spaces using a single supply duct. San Francisco's International Building, seen in Fig. 12.69, employs a dual-duct system.

The mixing boxes (terminals; Fig. 12.103) in dual-duct systems are similar to those used in other terminal-control all-air systems but are generally

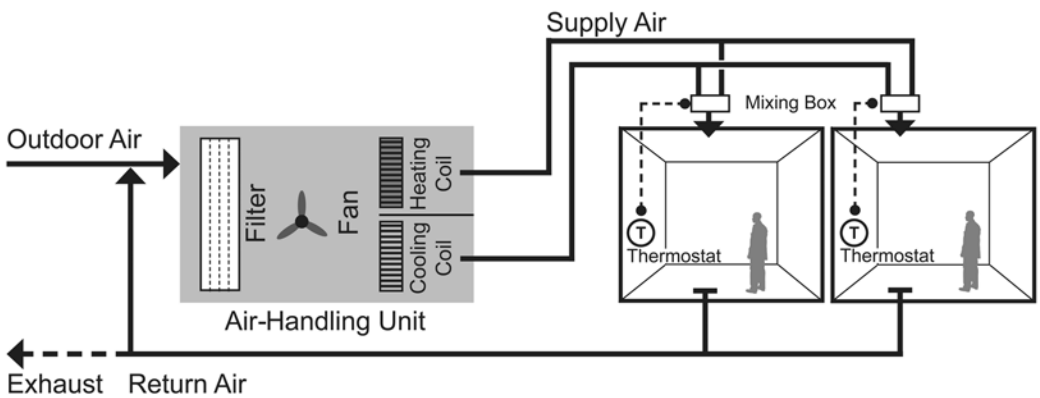
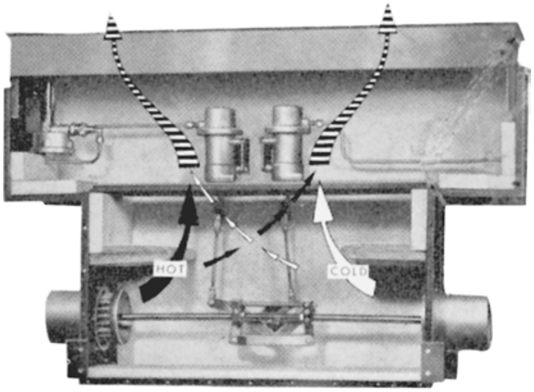
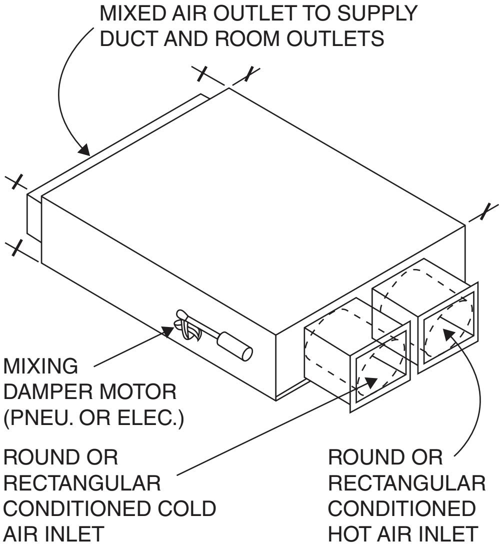


Fig. 12.102 *Schematic diagram of a dual-duct all-air HVAC system. Components are representative of a typical system installation. Note that two supply air ducts will run throughout a building. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*



(*a*)



(*b*)

Fig. 12.103 *High-velocity, dual-duct terminal providing mixing and attenuation (pressure and sound reduction). (a) Controlled from a thermostat, this unit blends the supply air streams and delivers air to the zone at the selected temperature. (Courtesy of Anemostat.) (b) Typical mixing box dimensions are: 10 by 50 by 30 in. (250 × 1270 × 760 mm) for a 400 cfm (190 L/s) unit to 18 by 60 by 66 in. (460 × 1520 × 1680 mm) for a 5000 cfm (2360 L/s) unit. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *9th ed.; © 1994 by John Wiley & Sons, Inc. Reprinted with permission from John Wiley & Sons, Inc.)*

larger for the same airflow capacity. This adds still more to the system impact on building volume. Although most dual-duct systems are constant volume, they can be configured as VAV when the reduction in airflow is no more than 50% below the maximum. For details on other dual-duct variations, see Grondzik (2007).

Variable air volume (VAV) system: This system (in a single-duct configuration, Fig. 12.104) is the most popular large-building HVAC system of recent years. Its single supply duct requires less building volume for distribution than do multiduct systems, and control of space conditions through variation of air volume flow rate (rather than of air temperature, as with a constant-volume system) saves energy (reductions in airflow greatly reduce fan power). Because of the nature of the control logic (basically, a reduced load means a reduced airflow), VAV air-handling systems tend to be cooling-only systems. Space heating needs are commonly picked up by a supplemental heating system (such as hydronic baseboard radiators or reheat coils at the VAV boxes). Automatic controls (linked to each zone's thermostat) adjust the supply air volume admitted to each zone through the action of a VAV box (terminal) located near the zone. The control logic is based upon the equation for heat transfer via air:

$$\text{heat transfer} = \text{airflow rate} \times \text{delta } t \times \text{conversion factor}$$

A constant-volume system varies delta t to address varying loads; a variable air volume system varies airflow rate. Same result (almost); different means.

Design of a successful VAV system demands attention to space load dynamics. A space with little load variation over time (such as an open-plan office space) will experience little change in airflow over time—and little energy savings from fan power reductions. A space with more dynamic load patterns will result in greater fan power savings, but the details of part-load control, supplemental heating, and indoor air quality maintenance become more intriguing. When a VAV box starts to reach full closure, little outdoor air will be delivered to the space—this may (or may not) affect IAQ acceptability. The devil is in the details.

With a VAV system, provision must be made for at least code-minimum fresh air levels during occupied periods, sometimes resulting in overcooling or wasteful reheating. The changing airflow in a VAV system results in changing noise production (which varies with airflow), and variable noise sources are inherently more noticeable than steady sources.

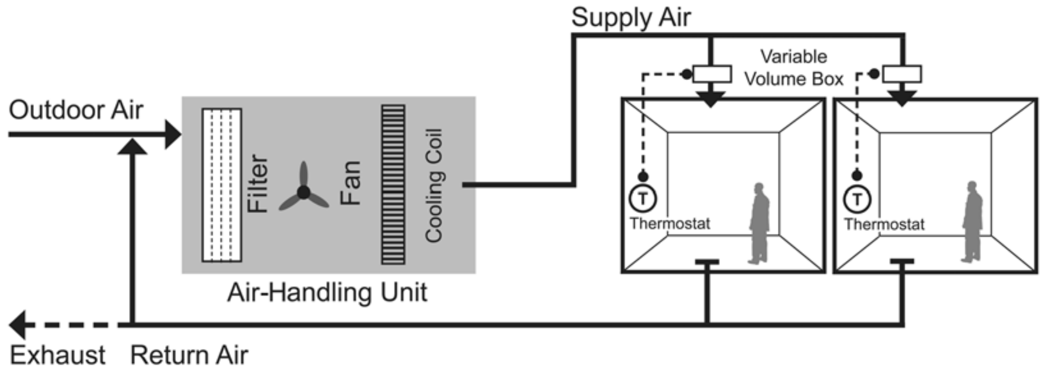


Fig. 12.104 *Schematic diagram of a VAV all-air HVAC system. Components are representative of a typical system installation. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

VAV terminal boxes are often placed above a suspended ceiling or below a raised floor adjacent to the zone being served. A fairly typical VAV box is shown in Fig. 12.105. This terminal serves not only to vary the quantity of air, but also to attenuate noise and reduce the speed of air before entry to the space. High-velocity distribution is common in main ducts because it reduces the size of the distribution tree.

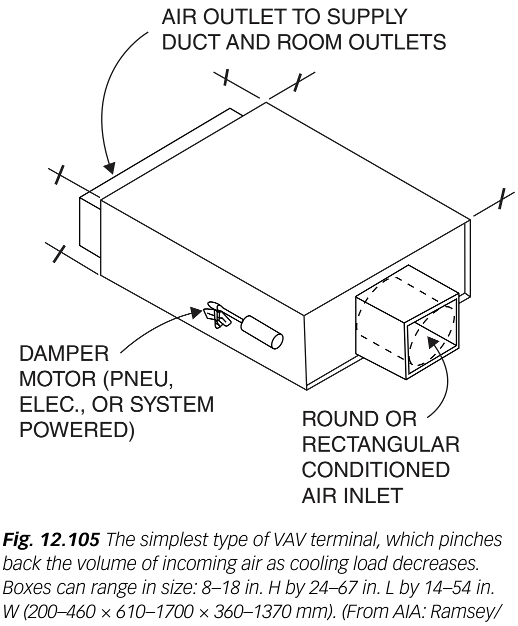


Fig. 12.105 *The simplest type of VAV terminal, which pinches back the volume of incoming air as cooling load decreases. Boxes can range in size: 8–18 in. H by 24–67 in. L by 14–54 in. W (200–460 × 610–1700 × 360–1370 mm). (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *9th ed.; © 1994 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

The Utah Department of Natural Resources in Salt Lake City (Fig. 12.106) utilizes a VAV system throughout its three-story, 105,000-ft^2 (9755-m^2) office building. Air is supplied from linear ceiling diffusers located between the rows of indirect luminaires parallel to the windows. Return air is taken into the suspended ceiling plenum. Highly insulated walls, windows, and roof lessen the need for perimeter heating, although a supplementary warm water heating system is built in below the windows to offset perimeter heat losses. The lower 1 ft (300 mm) is a slot where room air is drawn in by convection, and a perforated metal grille at the top forms the windowsill.

The building is elongated east–west for best daylight access and control and winter solar gain; lightshelves even out the daylight penetration. With almost no east- or west-facing glass, the building relies on 4200 ft^2 (390 m^2) of south glass and 3800 ft^2 (353 m^2) of north glass to serve its 125-ft (38-m) width. Supplementary indirect lighting is controlled by photocells and dimming ballasts.

Utah's hot, dry summers permit a four-stage approach to cooling. First is an economizer cycle at lower temperatures; next, direct evaporative cooling is used; then, indirect evaporative cooling (see Fig. 12.95), utilizing an oversized cooling tower; and finally (estimated at about 10 days per year), a conventional chiller.

An example of a floor-by-floor VAV system (Fig. 12.107) is a 1-million-ft^2 (92,900-m^2) 28-floor Chicago office building designed by Skidmore, Owings & Merrill. This mid-rise approach to office towers utilizes three "stacked" atriums to relieve

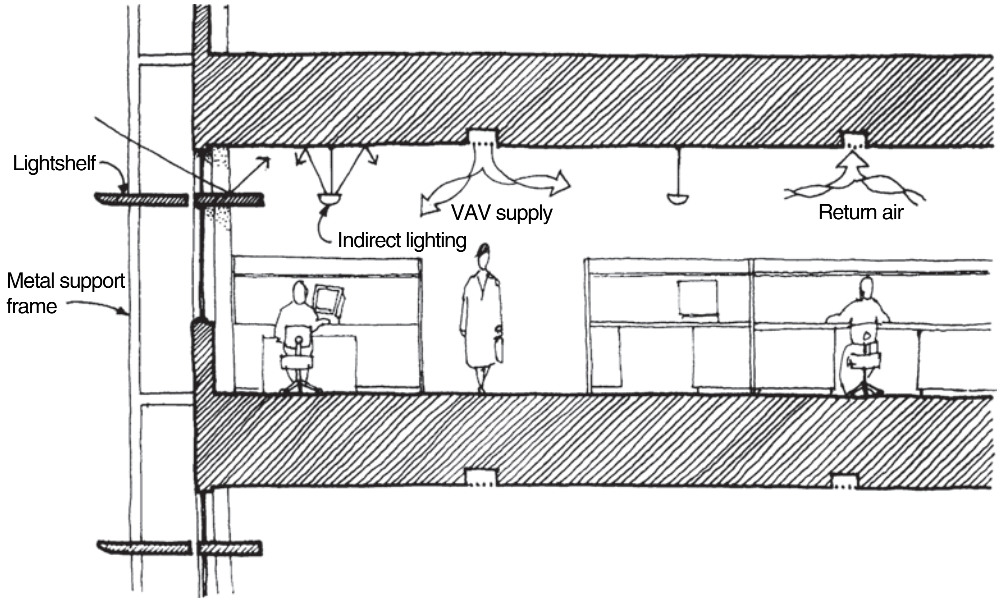


Fig. 12.106 The Utah Department of Natural Resources building features lightshelves, direct and indirect evaporative cooling, and an economizer cycle. Supply air is distributed by a VAV system with ceiling diffusers located between luminaires. (Based upon the design by Gillies Stransky Brems Smith Architects, Salt Lake City, UT.)

the monotony of the wide interior floors. Another result is lower structural and energy costs per unit floor area relative to conventional high-rise structures. The cubelike shape of the building exposes less skin area (38% of which is in insulating glass) to Chicago's cold winters; electric lighting at about 1.8 W/ft^2 holds down internal heat gains. To accommodate the differing schedules and comfort needs of a variety of tenants, each floor is provided with two VAV supply air handlers that can be operated at night and on weekends, independently of the rest of the building. Each floor's mechanical core has one exterior wall (on an alley) to facilitate fresh air intake/stale air exhaust. The perimeter heating system is electric resistance fin radiation; an economizer cycle provides cooling with outdoor air below 55°F (13°C).

Several variations on the basic VAV system have emerged, some of which respond to the problem of minimum airflows for rooms with little thermal load or to the desire to serve both interior and perimeter areas with the same HVAC system.

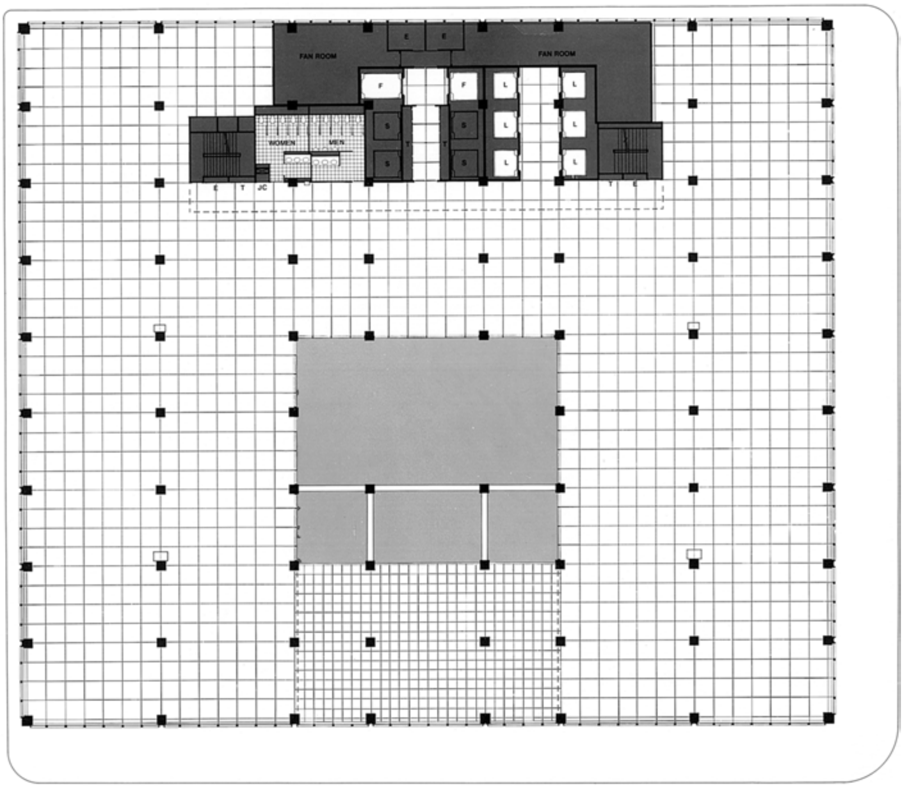
Fan-powered VAV terminals: Under low loads, cool air from the AHU is reduced to the minimum flow required for acceptable indoor air quality, while the unit's built-in fan draws additional "supply" air from a ceiling (or floor) plenum, heating it as required to meet space conditions. This variation allows individual terminal units to heat when the main supply system is cooling; it might logically serve perimeter zones.

Minimum closure VAV terminals: To maintain minimum fresh air flows, VAV terminals are usually set so that they cannot be entirely closed off, ensuring some outdoor airflow at all times while the system is operating. If this minimum airflow, entering at low velocity, does not provide the desired air motion and mixing within the room, VAV terminals can be equipped with fans, which are activated as needed in response to decreasing supply air volume. These self-contained fans mix room air with centrally supplied air to provide an air stream of the right temperature and velocity to maintain comfort.

Induction VAV terminals: An induction-type VAV terminal induces plenum air (heated by electric lighting) to mix with the incoming cool supply air stream.

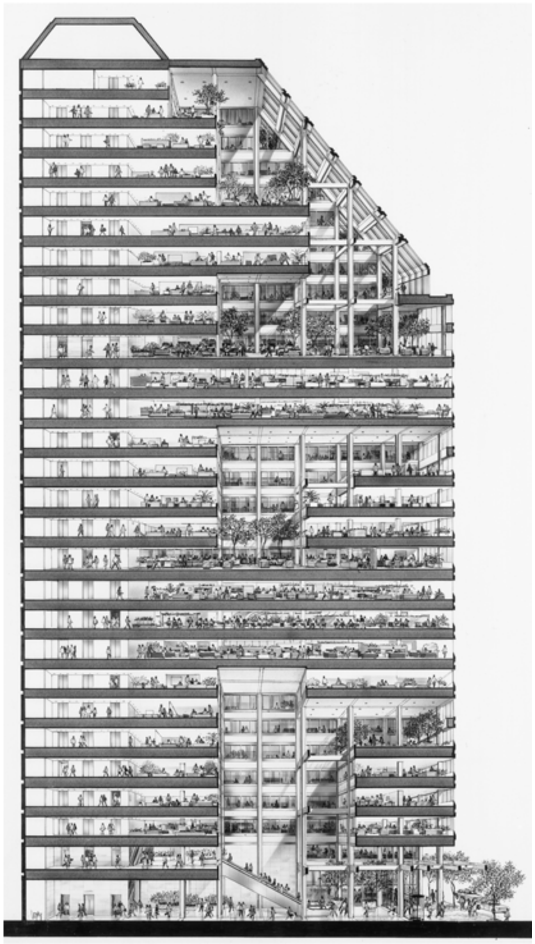
Reheat VAV terminals: Large space heating loads often require the use of reheat terminals

(a)



(b)

Fig. 12.107 *Floor-by-floor fan rooms supply a VAV system for this Chicago office building. (a) Exterior view of 33 West Monroe. (Photo by Merrick, Hedrick-Blessing.) (b) Plan of a typical lower floor; two fan rooms occupy the space along the exterior wall. (c) Section perspective showing stacked atria. (Courtesy of Skidmore, Owings & Merrill, Architects-Engineers, Chicago.)*



(c)

Fig. 12.107 (Continued)

supplied by hot water or electric resistance. This type of reheat application is more energy efficient than a standard constant-volume reheat system because a much smaller volume of air is first cooled, and then reheated. Water or electric coils can be incorporated in the VAV terminal or in the ductwork between the terminal and the room diffusers.

(b) Air–Water Systems

Several variations of air–water systems are fairly regularly used in current building designs. Because both air and water are used as heat-transfer media, these systems tend to be more complex than an all-air or all-water system. The logic behind an air–water system is that it brings in the best of both media. Air distribution allows for mitigation of indoor air pollutants through delivery of outdoor air. Water distribution allows for a substantial reduction in the size of distribution conduits. Air–water systems are fully functional HVAC systems that can produce comfortable results while effectively regulating IAQ, temperature, and humidity at reasonable first cost and with acceptable energy efficiency.

Often the amount of supply air delivered from the central AHU is the minimum required to accomplish IAQ control. This is generally (and very roughly) around 10% of the airflow required in an all-air system—thus the smaller ductwork sizes. Return air is minimized or eliminated in an air–water system since it is a 100% outdoor air system by definition. The bulk of space heating and cooling loads are handled by the water side of the system. This includes latent cooling and the resultant condensation of water that is removed from the room air (and must be disposed of). The central supply air may be delivered to the zones in a neutral condition (near room temperature) or be delivered heated or cooled to assist with space conditioning.

A signature aspect of an air–water system is an in-space delivery device—even though these devices cover a range of configurations. Preplanning and coordination are important to avoid conflicts and undesirable compromises regarding placement of delivery devices during construction. Maintenance of these delivery devices will occur in occupied spaces. Unit filters will be changed in the spaces (not in a central fan room). Fan-powered systems (such as a fan-coil) may present acoustical challenges since the fan is located in an occupied room.

Exhaust air may be gathered in a centralized duct system, making heat recovery possible. Or (as a cheaper alternative) air can be exhausted locally to avoid the construction of yet another distribution tree. If the water-side system permits only heating or only cooling, then a two-pipe system will work. If simultaneous heating and cooling is necessary to meet the owner's project requirements, then a four-pipe system is necessary. Three-pipe systems are a lower-first-cost alternative, allowing simultaneous heating and cooling (from two supply pipes with a single return pipe), but they waste energy by mixing hot return and cold return water flows in one return pipe. They are no longer permitted in most locales.

Induction system: Induction terminals (the delivery device) are typically located either below perimeter windows (Fig. 12.108) or above a suspended ceiling. The need to dispose of condensation

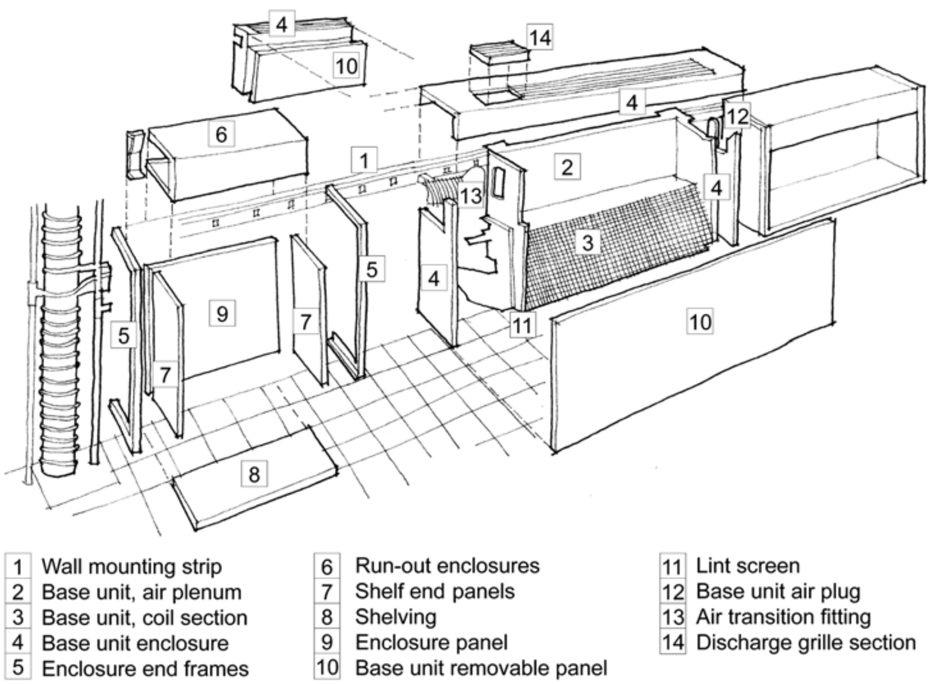


Fig. 12.108 *Assembly of a high-velocity induction unit. Conditioned 100% outdoor air is brought in through a high-velocity duct to provide ventilation and to induce the circulation of room air. Air is attenuated and silenced in the chamber (2), and then, through jets in the front of the plenum, it induces the flow of room air, which is heated or cooled at the coil (3). The lint screen "filter" (11) requires periodic maintenance for proper airflow and IAQ performance. (Courtesy of Carrier Corporation. Redrawn by Erik Winter.)*

from the cooling coil and to clean the unit filters makes under-window locations much easier to maintain, even if they intrude on the floor area available for occupancy. In a two-pipe system, either hot or cold water—not both—is available to deal with room loads under command of a thermostat linked to each terminal. Because cool air is distributed for most of the year, a two-pipe system is largely in heating mode in colder climates. Switch-over for two-pipe systems is a big deal—and a source of frequent occupant complaints. Switch-over is a slow process and is often scheduled without regard to actual weather conditions. In a four-pipe system, the simultaneous availability of hot and chilled water makes it possible to switch instantly from heating to cooling for excellent thermal control.

A schematic diagram of an induction system is shown in Fig. 12.109. A high-velocity (and high-pressure), constant-volume air supply is delivered to each terminal from a central AHU. At the terminal it is forced through an opening in such a way that air within the room (secondary air) is *induced* to join the incoming jet of supply air. The terminal mixes 20% to 40% supply (fresh) air with the 80% to 60% room air. The combined air stream passes over finned tubes for heating or cooling and is introduced into the space. Thermostats control the induction unit output by controlling either the flow of the water or the flow of secondary air.

The CBS Tower in New York City (Fig. 12.110) uses a high-velocity induction system for its perimeter zones. The triangular black granite-faced exterior columns give the façade a three-dimensionality quite unlike the slick glass boxes of its contemporaries (it was designed by Eero Saarinen and built in 1962). These thick columns enclose the perimeter distribution trees; every other column contains a high-velocity air supply; in between, every fourth column contains an HVAC water supply and every alternate fourth column a water return. The constant column sizes belie the thicker air, thinner water distribution trees. The interior zone of this tower is served by a VAV system; return air from both perimeter and interior zones is collected at the core.

Fan-coil system with supplemental air: This system (Fig. 12.111) is conceptually similar to the preceding induction system. The air and water sides of the system, however, are delivered to the spaces individually—water through a fan-coil device and air through diffusers. A fan, rather than high-velocity primary air, is used to circulate room air through the unit. Fan-coils are very commonly employed in a variety of building types and are available in a range of configurations to accommodate such usage. Vertical, horizontal, and stackable units are available (Fig. 12.112).

Fan-coil units are inherently noisy due to the operation of the fan, so careful attention to sound ratings is required when background sound levels must be low. In offices, a relatively high background sound level can help to maintain acoustic privacy at the workstation. The sound of the fan may also provide perverse reassurance that some kind of air-conditioning system is at work.

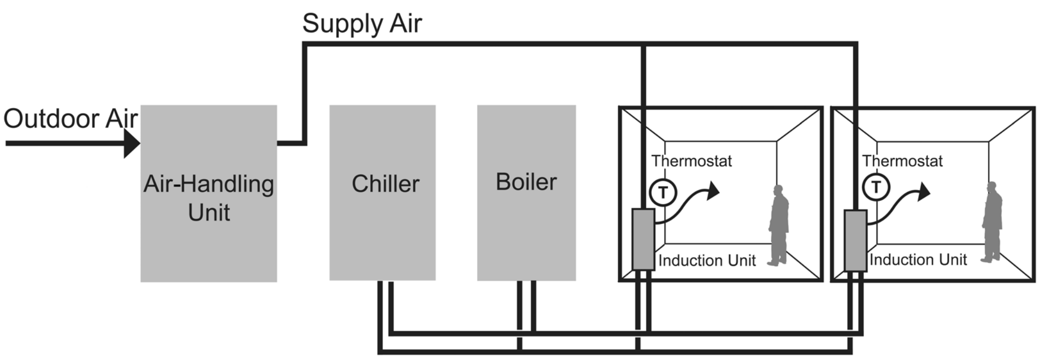


Fig. 12.109 *Schematic diagram of an induction air–water HVAC system. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

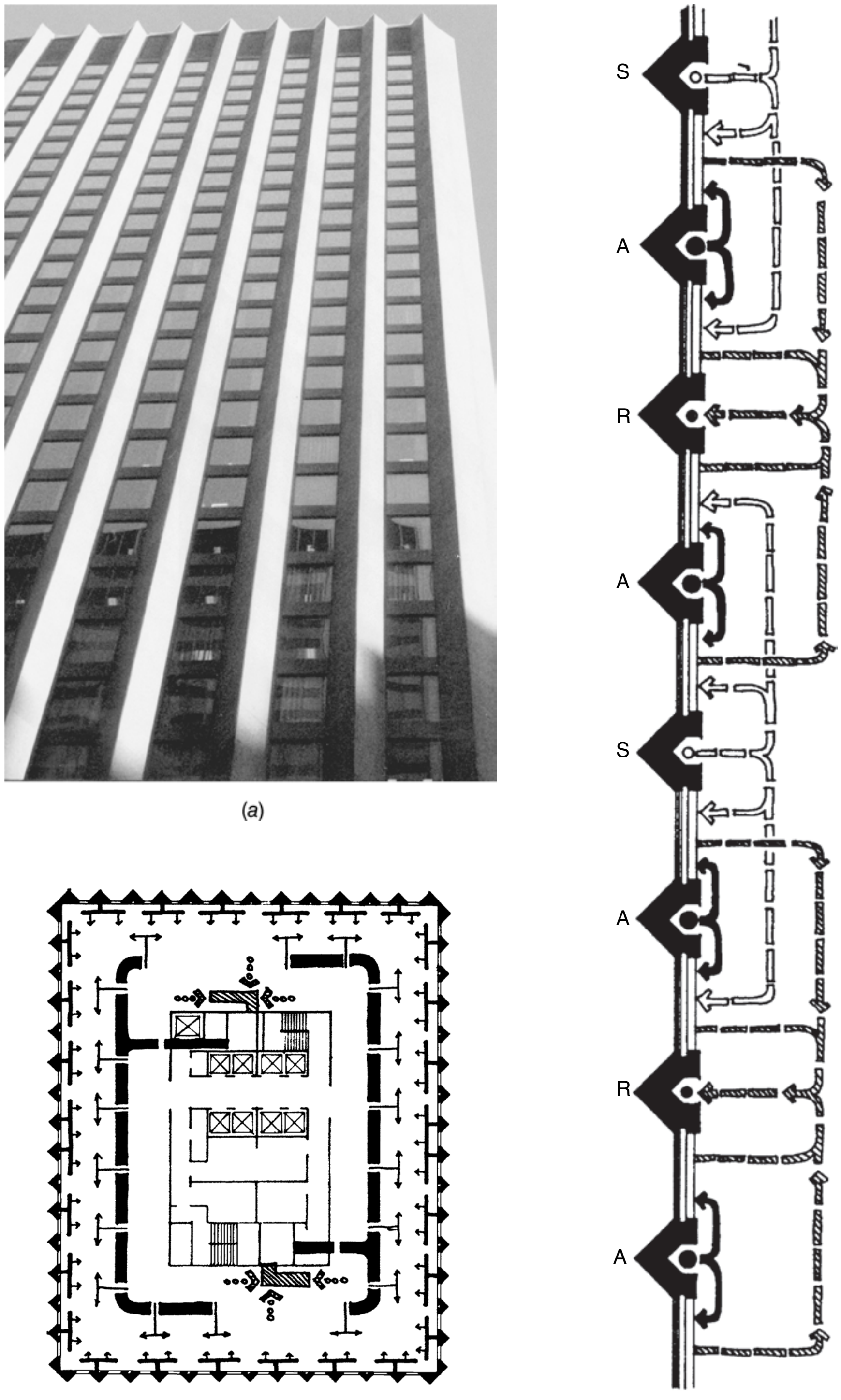


Fig. 12.110 *The identical triangular exterior columns of the CBS Tower in New York City (a) enclose a variety of distribution trees. (b) Plan of a typical floor; perimeter zones are served by an induction air–water system, interior zones by a VAV all-air system. All return air is collected at the core. (c) At the perimeter, column type A contains an air supply tree feeding the induction units on either side of the column. Column type S contains the supply water tree, hot in winter and cold in summer. Column type R contains the return water tree. (From David Guise,* Design and Technology in Architecture; *© 1985, John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

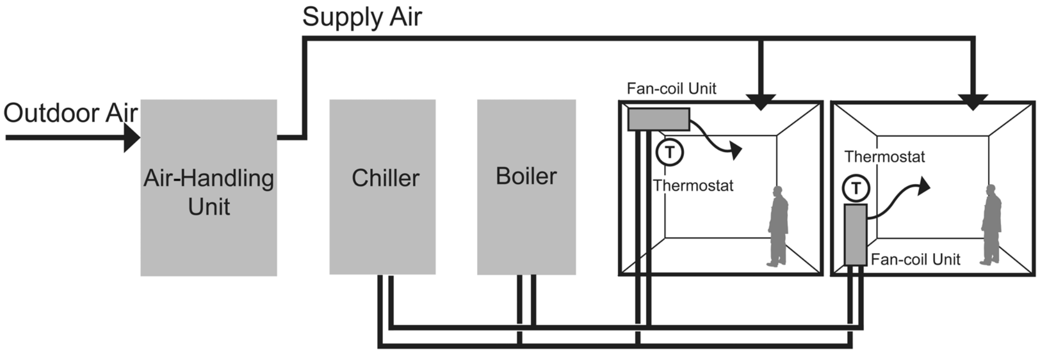


Fig. 12.111 *Schematic diagram of a fan-coil air–water HVAC system. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

Radiant panels with supplemental air: Radiant heating systems have a large following of comfortable users; radiant cooling systems are fairly commonly used in Europe and are getting a closer look in the United States. Radiant panels combined with a central air supply are another form of air–water HVAC system (Fig. 12.113). Warm surfaces can be used to offset envelope heat losses. Cool surfaces can be used to offset internal heat gains and/or envelope heat gains. The ceiling is often favored as a radiant panel location, because it is uncluttered by furniture, carpet, tackboards, and the other items that regularly cover floors and walls. Chilled beams are a variation on radiant panels. Dedicated outdoor air systems (DOAS) are a variant on supplemental air systems. Chilled beams with DOAS are an emerging design trend. At the 56-story Commerzbank in Frankfurt, Germany, chilled ceilings serve all office floors in conjunction with a ventilation system.

A building that uses radiant panels (in offices) and fan-coil units (at entries) is shown in Fig. 12.114. Green on the Grand is a 23,465-ft^2 (2180-m^2) two-story office complex in Kitchener, Ontario. Its design combines a very highly insulated envelope, daylighting, water conservation, a gas absorption (non-CFC, non-HCFC) chiller/heater with a heat rejection pond, a separate IAQ system, and heat recovery of exhaust air. It also features a dedicated outdoor air system for ventilation and a hydronic system for heating and cooling. The hydronic system uses fan-coils at the entryways and radiant panels at ceilings of office spaces. Fan-coils are able to handle the extremes of entryway heat losses and gains. The radiant panels in the offices are used for both heating and cooling, but are sized based upon cooling loads and cover 30% of the ceiling area. Tenants were given their choice of two designs: steel panels suspended below a drywall ceiling (painted to match the ceiling color) or extruded aluminum panels fit into a suspended ceiling system. To prevent condensation on these radiant panels during cooling mode, the ventilation air is dehumidified.

The ventilation system supplies air low on the walls and exhausts high on the walls, an informal form of displacement ventilation. There are two rates of outdoor air delivery: 20 cfm (10 L/s) per person, and (when economizer cycles operate or when more fresh air or more cooling is required) 40 cfm (20 L/s) per person. The exhaust air flows through two heat exchangers: The first reheats outdoor air that has been deeply cooled for dehumidification; the second preconditions the incoming outdoor air at the point of entry. The latter heat exchanger is a rotary-wheel ERV capable of transferring both heat and moisture.

Several approaches to radiant cooling (and heating) panels, independent of a dehumidified air supply, are shown in Fig. 12.115. These approaches assume a minimal floor/ceiling thickness, which could contribute either to reducing the floor-to-floor height or to greater ceiling height (for daylight penetration or displacement ventilation).

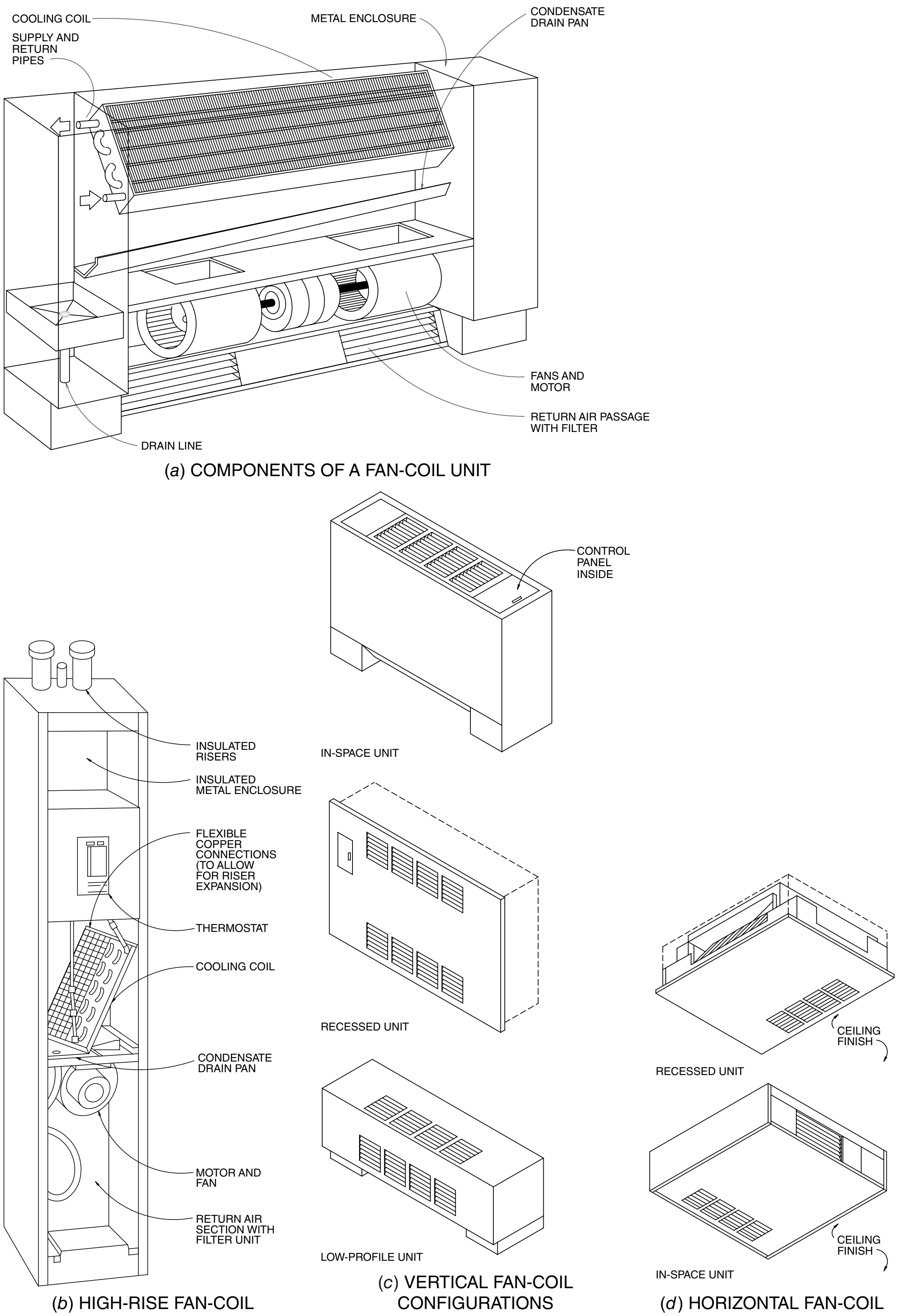


Fig. 12.112 *(a) The innards of a standard below-window fan-coil unit without outdoor air connection. Widths can range from 2.5 to 7 ft (0.8 to 2.1 m), height is around 26 in. (660 mm), and depth between 9 and 12 in. (230-305 mm). (b) High-rise unit for corners or cabinet locations. These can be stacked to reduce connecting piping runs and simplify condensate collection. (c) Vertical units for below windows. Low-profile unit height is around 14 in. (360 mm). (d) Horizontal units for above-ceiling locations. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 10th ed.; © 2000 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

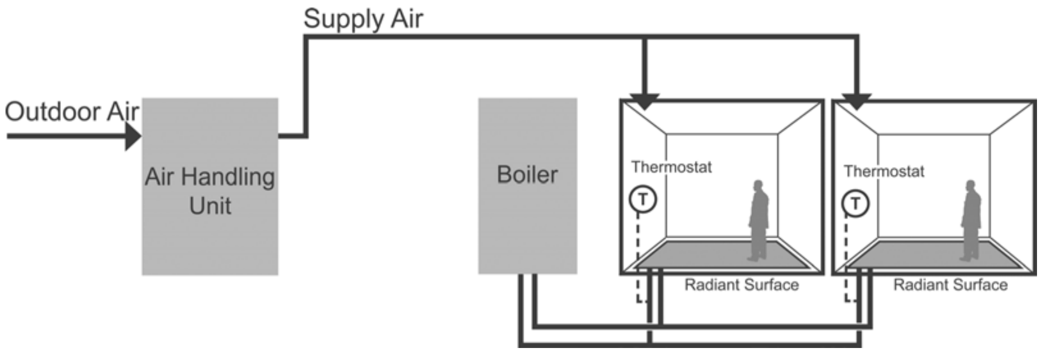


Fig. 12.113 *Schematic diagram of an air–water HVAC system employing radiant panels and supplemental air supply. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

If a raised floor is used above these concrete slabs, even higher percentage heat gains come from the ceiling.

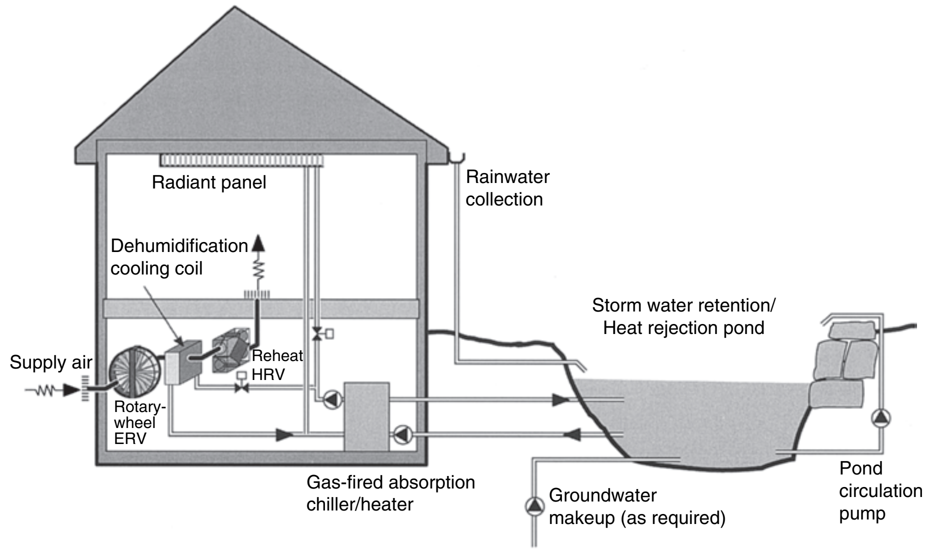
Radiant floors are sometimes used for cooling, as in the Bleshman Regional Day School (Fig. 12.116). The designers of this school for the disabled recognized that the majority of its users would spend much of their time quite close to the floor and that colder air near the floor could be uncomfortable, especially during New Jersey winters. The entire floor is warmed by supply ventilation air in winter; the air enters just below windows to counteract the downdraft off cold glass surfaces. In summer, the cool supply air first cools the floor and then cools the air in front of the warm glass. The concrete cellular "air floor" provides thermal mass that helps maintain steady temperatures. Heated or cooled air is provided by rooftop air-source heat pumps, one of which is provided for each cluster of three to six classrooms.

(c) All-Water Systems

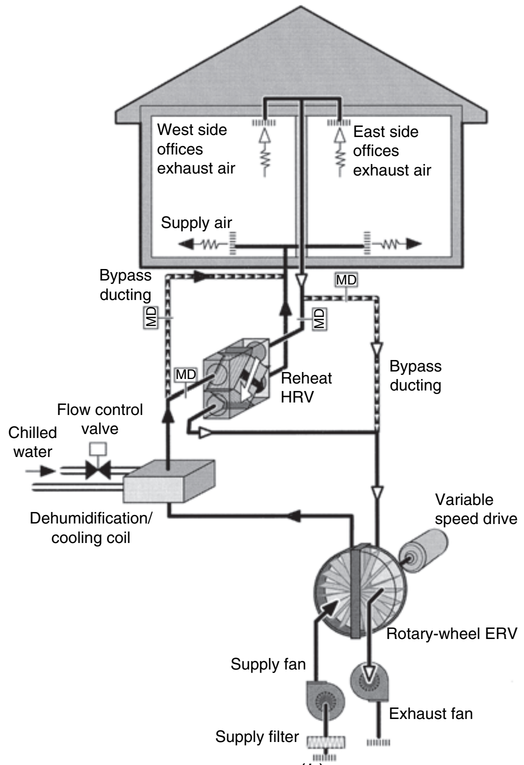
As the name implies, an all-water system distributes heating and cooling effect from a central location to the various zones using only water. No air supply is provided by a central system. Although requiring the least amount of space for distribution of any central HVAC system, lack of a structured approach to supply air makes this type of system highly suspect with respect to indoor air quality. In most nonresidential applications, an all-water system (without a means of air supply) cannot meet the ASHRAE definition of an air-conditioning system. All-water systems must be considered with caution, even though they may be appealing in retrofit projects, historic renovations, or new projects where bad planning leaves no room for distribution elements.

A schematic example of an all-water system is shown in Fig. 12.117. There is no air-handling unit or ductwork tree. Indoor air quality is dealt with locally—by means of infiltration, or through windows, or by use of a delivery device that connects to the outdoor air via a penetration through the building wall (termed a unit ventilator). Any of the many water-based terminal devices may be used with an all-water system—radiant panels, fan-coil units, valence units, baseboard radiators, and so forth.

Provision of outdoor air (as with an all-water system) may take the simple form of operable windows. An expressive variation on this approach appears in the reading rooms and staff workrooms for the Seeley G. Mudd Library at Yale University (Fig. 12.118). Limestone spandrels are curved in to allow outdoor air to enter these perimeter rooms just below the windows, where hot water finned-tube radiators are available to provide heating as needed. The incoming outdoor air replaces exhaust air, which flows out of the upper operable windows. The remainder of the building has conventional forced-air heating and cooling.



(*a*)



(*b*)

Fig. 12.114 *An innovative Canadian office building, Green on the Grand at Kitchener, Ontario. The cooling system combines a radiant panel system (a) with a summer ventilation dehumidification system (b). The building also features daylighting, a gas absorption chiller/heater, rainwater storage pond heat rejection, and two-stage heat recovery. (Courtesy of Enermodal Engineering, Ltd., Kitchener, ON.)*

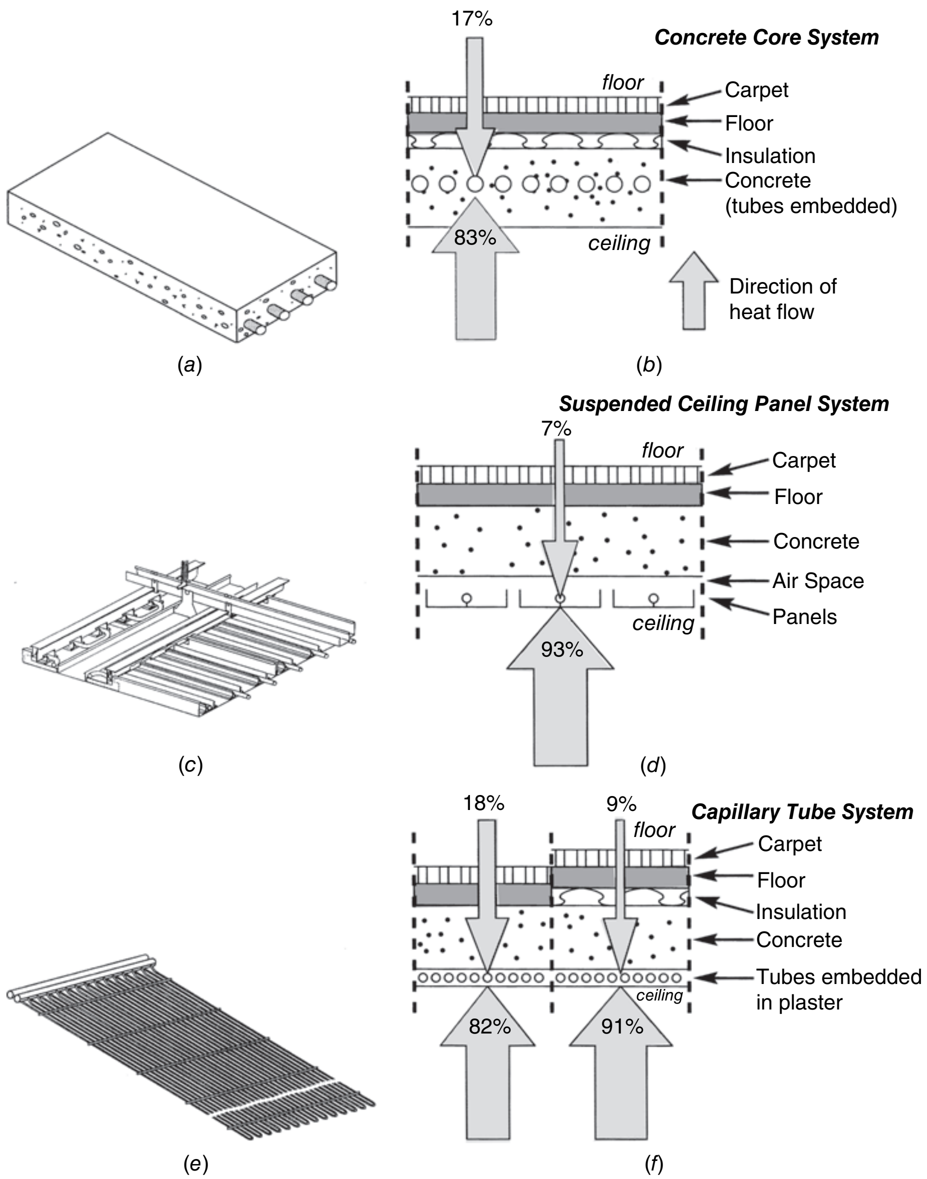


Fig. 12.115 *Approaches to radiant cooling systems. (a) Concrete core system: water is circulated through plastic tubes embedded in the concrete floor/ceiling slab. (b) With carpet, pad, and insulation on the floor, most of the heat radiates to the ceiling. (c) Panel system, usually using aluminum facing, connected to metal tubes. (d) Panel system has the highest percentage of heat to the ceiling. (e) Cooling grid made of capillary tubes embedded in ceiling plaster (or in gypsum board or mounted on ceiling panels). This provides the most even surface temperature distribution. (f) A high percentage of heat is radiated to the cooled ceiling, depending on the use of insulation below the carpet and pad. (From* Center for Building Science News*, Fall 1994. Lawrence Berkeley Laboratory, CA.)*

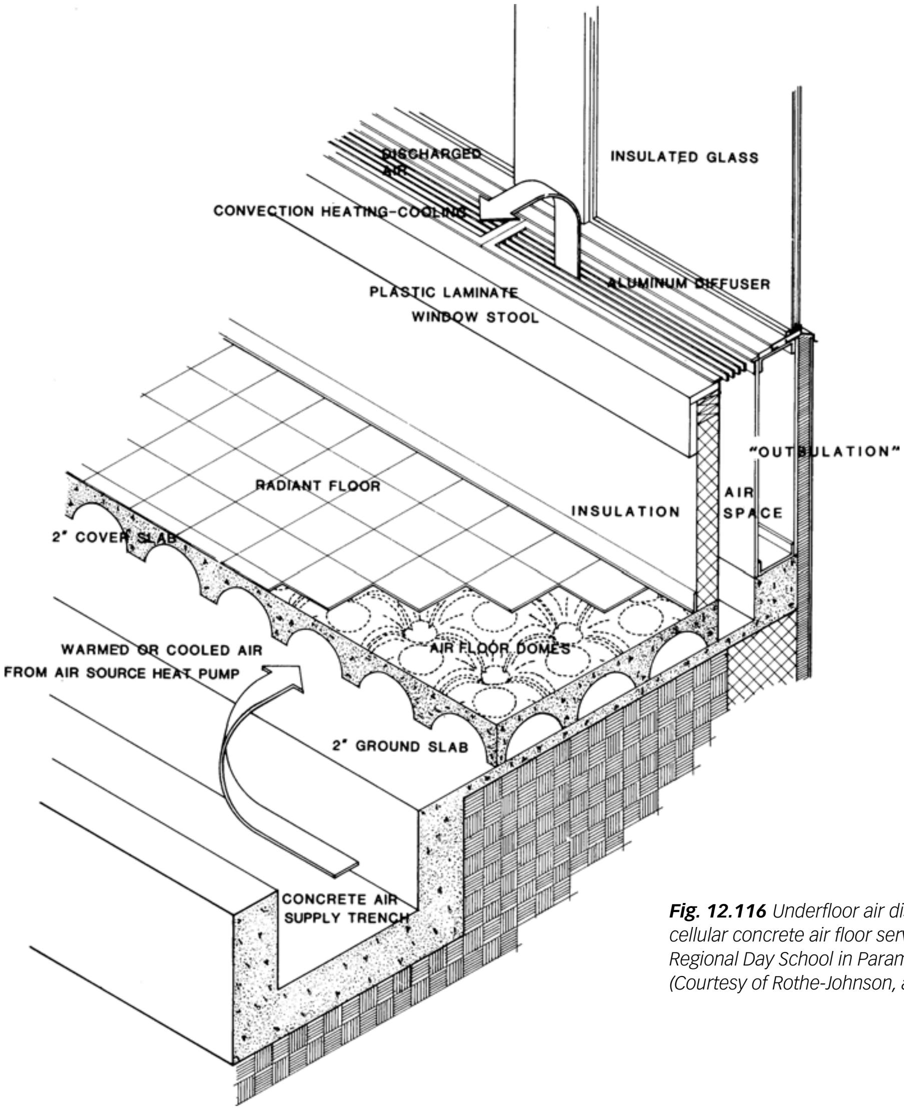


Fig. 12.116 *Underfloor air distribution using a cellular concrete air floor serves the Bleshman Regional Day School in Paramus, New Jersey. (Courtesy of Rothe-Johnson, architects.)*

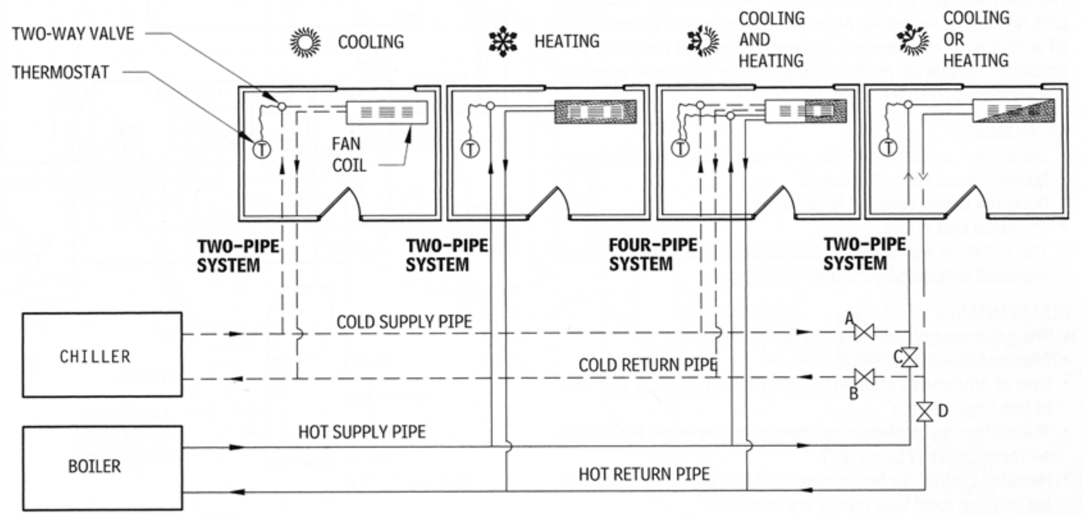
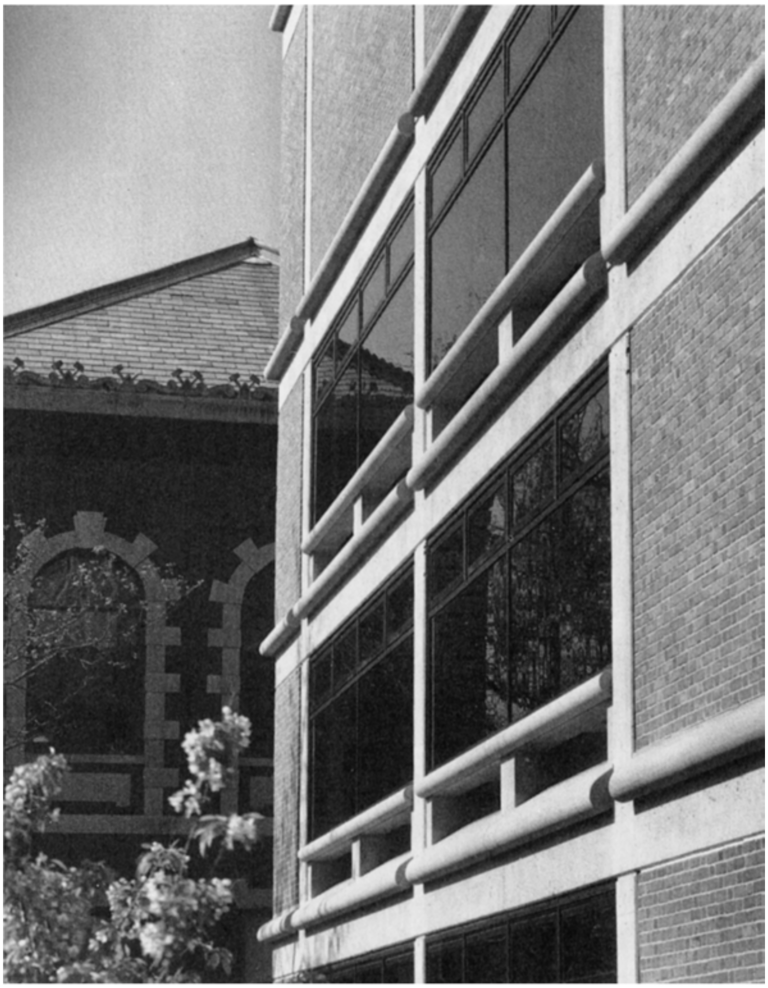
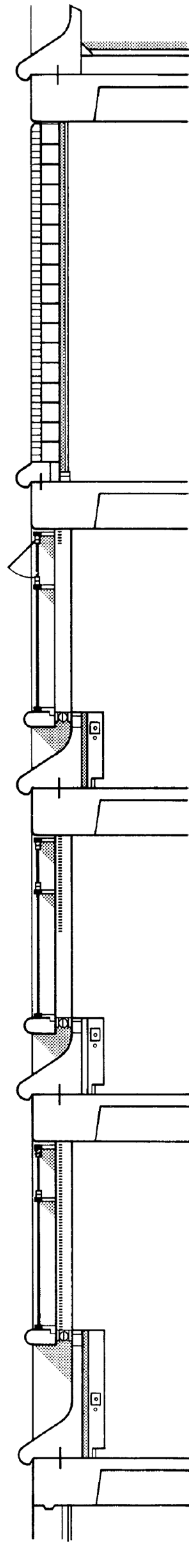


Fig. 12.117 *Schematic diagram of an all-water HVAC system (with a four-pipe distribution arrangement). (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*



(a)



(b)

Fig. 12.118 *Local outdoor air intake with finned-tube radiation. The Seeley G. Mudd Library at Yale University; Roth and Moore, architects. (a) Exterior, showing curved limestone spandrels, along which flows incoming outdoor air. (Photo © Steve Rosenthal.) (b) Section showing the fresh air intake, finned-tube radiation, and upper operable sash for exhaust air. This system is used for the smaller reading rooms and staff workrooms at the building perimeter.*

12.19 TRENDS IN HVAC SYSTEMS DESIGN

During the second decade of the twenty-first century, several trends appear to be bubbling in the world of HVAC design. These are being driven by a desire to produce higher-performance buildings—deep green projects, net-zero energy projects, carbon-neutral projects. One trend that seems unavoidable if net-zero energy buildings are to become a reality is a willingness to let active systems partner with passive systems. No matter how efficient an active HVAC system, an appropriate passive system will use less energy (and renewable energy, to boot). One of the more direct paths to net-zero energy is not to reduce energy use for heating and cooling, but rather to eliminate such energy use. Building automation systems make the integration of active and passive systems easier to manage. There is still a lot to learn, however, about system and occupant responses to rapidly changing thermal conditions (as in a mixed-mode cooling system—one that blends air conditioning and natural ventilation). Effectiveness is as important as efficiency.

(a) Ground-Source Heat Pumps

Ground-source heat pumps are being used quite frequently in high-performance buildings. These are discussed in Section 12.8. All else being equal, changing to a ground-source heat pump system from any other active HVAC source approach should be able to reduce heating/cooling energy use by around 50%. This is a serious reduction in energy use and is attention-getting.

A late 1990s building just east of Central Park, in New York City, utilizes two wells 1500 ft (457 m) deep; all but the top 50 ft (15 m) of the wells are lined by bedrock. Heat is taken from (or discharged to) water, which is pumped from one well and discharged to the other—a "groundwater-source" system. The average year-round temperature in these deep wells (in an intensely urban area) is around 56°F (13°C), about the temperature at which chilled air is delivered to a space in summer. Going to such depths is perhaps the only ground-source option in densely built-up areas.

The Cambridge (Massachusetts) Cohousing Project (Fig. 12.119) is also located in a densely settled urban neighborhood. The 41 living units feature passive solar heating, underground parking (this preserves some 20,000 ft^2 [1860 m^2] of the surface for open green space), and centralized heating/cooling utilizing ground-source heat pumps with numerous thermal zones. In this urban setting, the relative quiet of the indoor heat pumps is a welcome amenity.

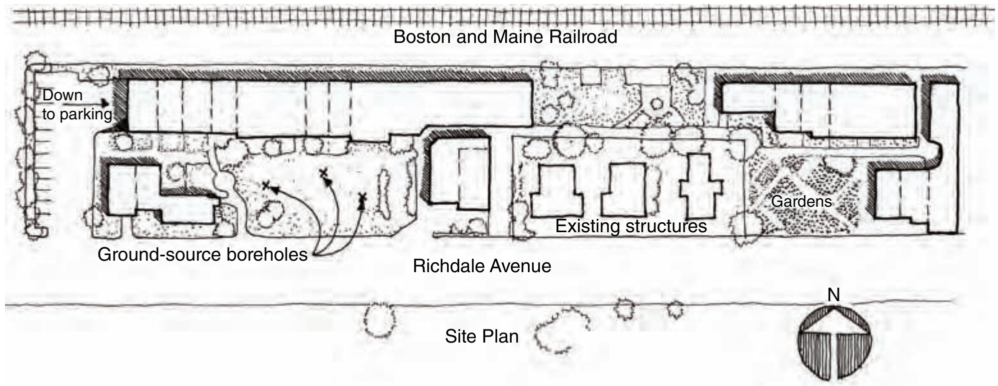
Ball State University recently replaced the coal-fired boilers (on-site combustion) and dedicated chillers (vapor compression refrigeration) that served as the source devices for campus climate control with a campus-wide (district) ground-source heat pump system. This major retrofit produced substantial environmental benefits and also provides ongoing energy (and cost) savings. The system uses two widely separated central plants, closed loop vertical bore holes, and underground distribution loops. A link to detailed information may be found in the References and Resources section of this chapter (Ball State University, 2013).

(b) Underfloor Air Distribution

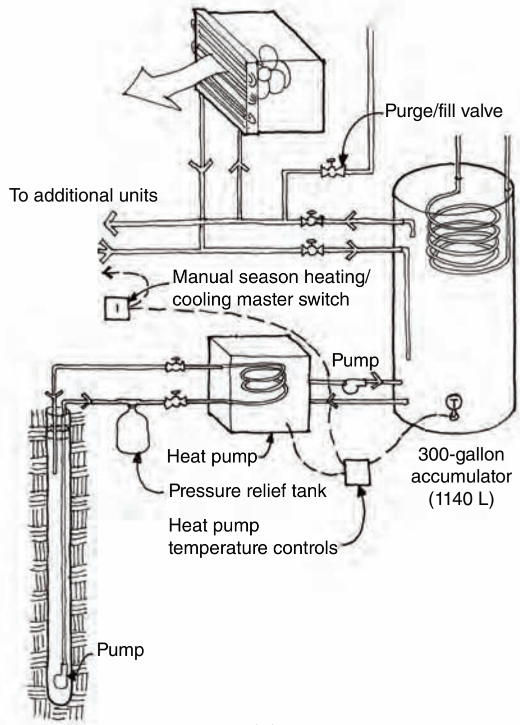
Underfloor air distribution (UFAD) systems are being promoted as an energy-efficient and air-quality-effective means of distribution for an HVAC system. The jury is still out on the ability of these systems to deliver on the promised benefits, but it is likely that they will become more common. ASHRAE released a revised design guide for UFAD systems (ASHRAE, 2013). Some background on underfloor air distribution may help explain this distribution/delivery option.

As open-plan office spaces have grown larger in area and their ceilings higher (for daylight penetration and indirect lighting), and as concerns about IAQ have deepened, the floor has gained in popularity as an air source location. Underfloor air supply introduces supply air (cooled to just below the design room temperature) through floor outlets, at a low velocity. Although independent of delivery location, outdoor air supply rates are typically near 45 cfm (22 L/s) per person, compared to the 30 cfm (15 L/s) or so often used with ceiling supply systems. This high-volume, low-Δt, low-velocity combination requires greatly increased duct sizes, essentially provided by using the plenum formed by a raised floor system as a duct. The supply air rises quickly to the occupied zone, drawn upward by a stack effect driven by heat gains from lighting, people, and office equipment, and by supply-air pressure. The air continues to the ceiling, where it is collected and returned to the air-handling unit. With the freshest and coolest air at the floor and the hottest and most stale air at the ceiling, this system promises better IAQ and thermal comfort than would be available from ceiling supply–return systems. Furthermore, adjustable outlets at the floor are easily reached by occupants.

The raised floor that forms the upper boundary of the plenum is typically a 2 × 2 ft (600 × 600 mm)



(*a*)



(*b*)

Fig. 12.119 *Cambridge (Massachusetts) Cohousing development takes advantage of three boreholes on its urban site (a) to provide central heating and cooling (via heat pumps), serving individual residential fan-coil units. The heat pump also preheats water (b) for the DHW (domestic hot water) system. The residences are sited to provide winter solar access, and an outdoor air intake is located on the side sheltered from adjacent railroad tracks. (Courtesy of Building Science Engineering, Harvard, MA.)*

module. The module elements that contain diffusers often also contain an outlet for power and data. If the diffuser is placed off-center within the module, each plan rotation of a module moves the outlet slightly, expanding the variability of the floor openings relative to furniture placement. Some codes restrict the height of the raised floor plenum; many codes require specially coated wiring within the plenum.

The overall floor-to-floor height needs to be great enough to accommodate both the raised floor and the higher office ceiling (at least 9 ft [2.7 m] to accommodate warm air stratification). However, elimination of supply air ductwork can also eliminate the need for a ceiling cavity. This tends to expose the lighting, fire sprinkler, and public address systems below the structural ceiling, although the latter can be distributed in the raised floor cavity above, puncturing the structural ceiling as required.

The structural slab below the raised floor can be of concrete, and this thermal mass can be night-ventilated to store coolth to assist with cooling for the next day. The Inland Revenue Building incorporates a night-ventilated raised-floor section within its precast waveform floor sections.

Library Square in Vancouver, British Columbia (Fig. 12.120), utilizes a raised floor to serve interior zones with book stacks. The library has seven floors, totals 390,000 ft^2 (36,320 m^2), and exposes the concrete structure as a finished ceiling. The floor-to-floor height is 16.4 ft (5 m). The underfloor supply is fed by VAV boxes and floor fan units (FFU) that blend low-temperature supply air (about one-third) with locally filtered return air (about two-thirds) to provide 63°F (17°C) air to the pressurized plenum. Flush to the floor, high-induction swirl floor diffusers (8 in. [200 mm] in diameter) produce an upward air motion, taking the supply air directly into the occupied zone (the first 6.5 ft [2 m] of height on each floor). The stack effect caused by heat from people, computers, and lighting takes hot air on to the stratification zone above. People-generated pollutants tend to rise to the hot, stale air zone, then into return air slots in the precast concrete ceiling. Return air is taken away in insulated ducts within the supply air plenum of the floor above. The plenum height is an unusually generous 2 ft (600 mm); it also contains the sprinkler distribution and all wiring systems. The warm, dry summer climate supports a night ventilation system, flushing the plenum and storing coolth in the exposed concrete structure. This has reduced the need to use an ice-storage system.

(c) Dedicated Outdoor Air Systems

Dedicated outdoor air systems (DOAS) were discussed briefly in Section 12.18(b). The basic idea behind a DOAS is to decouple control of indoor air quality from control of the thermal environment. This allows the two key objectives of an HVAC system to be designed independently and without conflicts. Although the idea has merit and has been

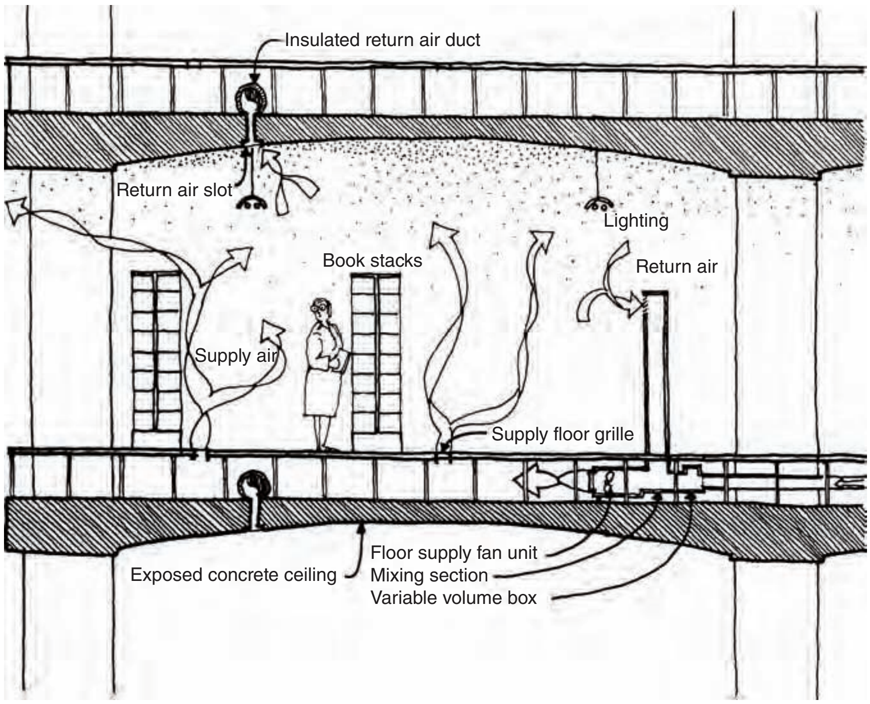


Fig. 12.120 *Library Square, Vancouver, British Columbia, supplies conditioned air to the central book stacks via an underfloor plenum. (Section adapted from information supplied by Blair McCarry, Keen Engineering, North Vancouver, BC.)*

developed in a number of projects, this is more of a potential than an actual trend. Increased first costs associated with two systems (versus one) appear to be slowing adoptions.

(d) Chilled Beams

Chilled beams (Fig. 12.121) are an approach to HVAC delivery that has substantial traction in Europe and the UK and polite interest in North America. Although often viewed as simply a form of radiant cooling device, chilled beams can also deliver cooling effect via convective heat transfer. Passive chilled beams are all-water terminals that exchange heat via radiation and convection; active chilled beams are air–water terminals with convective transfer predominating.

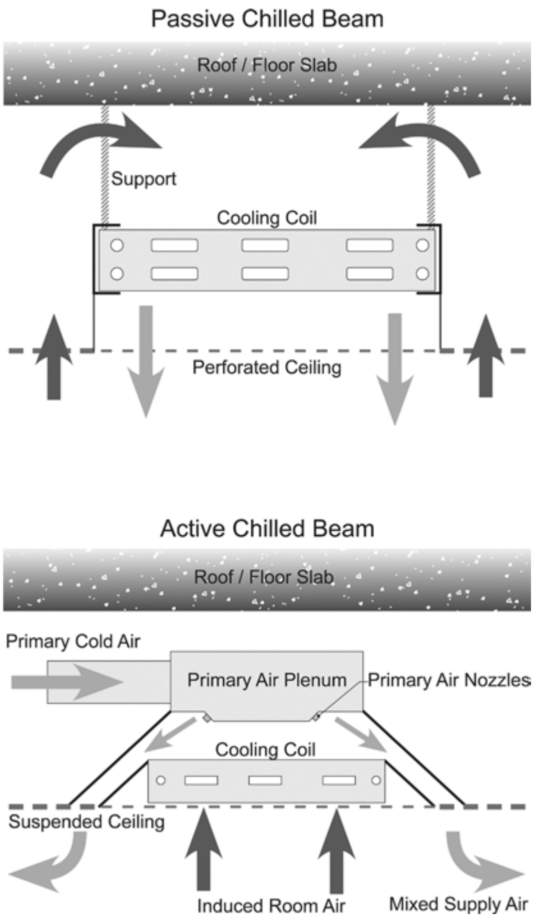


Fig. 12.121 *Active and passive chilled beams. (Drawn by Tyler Mavichien; © Walter Grondzik; all rights reserved.)*

12.20 ENERGY EFFICIENCY EQUIPMENT AND SYSTEMS

One major advantage of central systems with central equipment rooms is the opportunity they present for energy efficiency design moves. Regular maintenance is simplified when all equipment lives in a generous space with good environmental conditions; regular maintenance brings increased efficiency of operation. The opportunity for heat transfer between various systems and pieces of equipment increases greatly when the equipment is colocated and the systems can easily be connected. A few examples of heat transfer and/or heat reclaim opportunities follow.

(a) Heat Reclaim

Boiler flue economizers (Fig. 12.122) work by passing the hot gases in a boiler's stack through a heat exchanger; the collected heat is used to preheat incoming boiler water.

Runaround coils (Fig. 12.123) can be used to transfer heat between intake and exhaust air streams even when these two streams are rather far apart. The circulating heat-transfer fluid usually contains antifreeze and it provides simple sensible heat transfer, with no restrictions on locating air exhaust and air intake. No contamination of intake air is caused by this arrangement. The efficiency of such coils

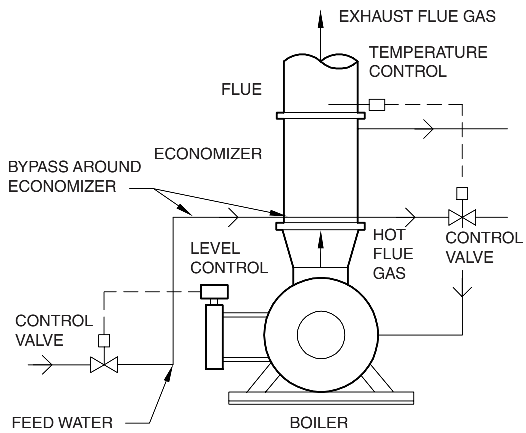


Fig. 12.122 *Heat recovery for boilers. Flue gas entering at 500°F (260°C) leaves the "economizer" at 325°F (163°C), a temperature still high enough to prevent condensation in the stack. The recovered heat is applied to incoming boiler water, raising its temperature from 200 to 248°F (93 to 120°C). (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

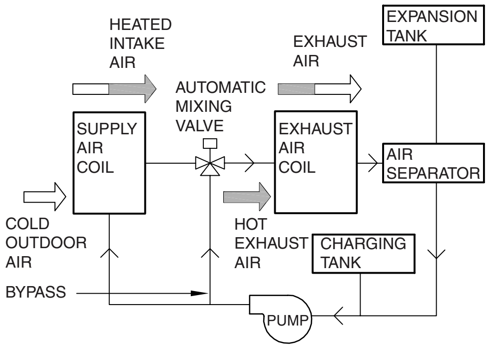


Fig. 12.123 *Runaround coils for heat transfer between outdoor air and exhaust air are used where the air streams are in separate locations. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 11th ed.; © 2007 by John Wiley & Sons, Inc. Reprinted with permission of John Wiley & Sons, Inc.)*

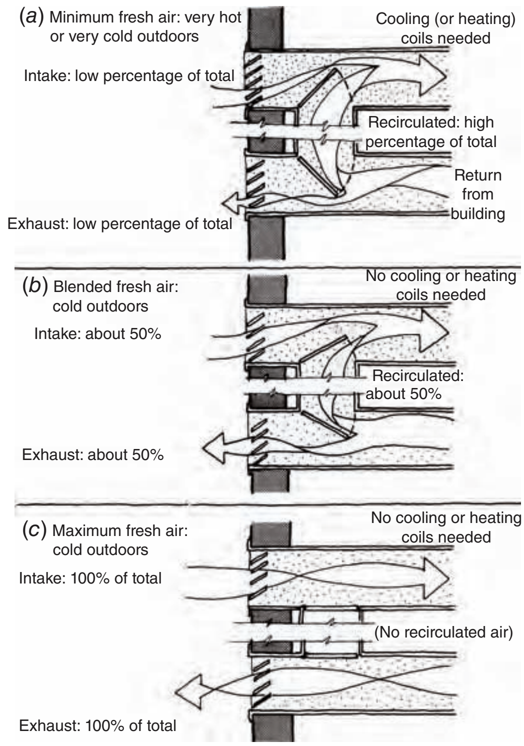


Fig. 12.124 *An economizer cycle controls the relationships among outdoor, exhaust, and recirculated air. (a) When outdoor air is too hot or too cold, the economizer cycle is inactive, and IAQ-minimum outdoor air is introduced. (b) As very cold outdoor air gets warmer, it can be blended with recirculated air, and neither heating nor cooling coils are needed. (c) When outdoor air is cool, it can completely displace the need for mechanical cooling.*

runs between 50% and 70%, and they are available in modular sizes up to 20,000 cfm (9440 L/s).

Heat recovery ventilators were discussed in Chapter 5. The term "heat recovery" denotes a sensible heat exchange device. Energy recovery ventilators (also called heat wheels) can exchange both sensible and latent heat (through use of a desiccant-coated exchange medium). These devices are typically used to transfer heat from an exiting air stream to an incoming air stream. Substantial energy savings can accrue from the use of such devices. These systems can be scaled to fit virtually any size of building.

(b) Economizer Cycle

An *economizer cycle* (Fig. 12.124) uses cool outdoor air, as available, as supply air. The economizer cycle can be thought of as a central mechanical substitute for an open window; when it is cool enough, 100% outdoor air can be provided as supply air, and no refrigeration is needed. When the outdoor air temperature is higher than the desired supply air temperature but lower than the return air temperature, 100% outdoor air is still brought in, but refrigeration is used to reduce its temperature. Above the return air temperature, outdoor air is reduced to the volume required for maintaining acceptable indoor air quality. Sensible and latent heat content affects the viability of using outdoor air in an economizer cycle. Although this discussion refers to temperature comparisons, comparisons of enthalpy should, in fact, be used.

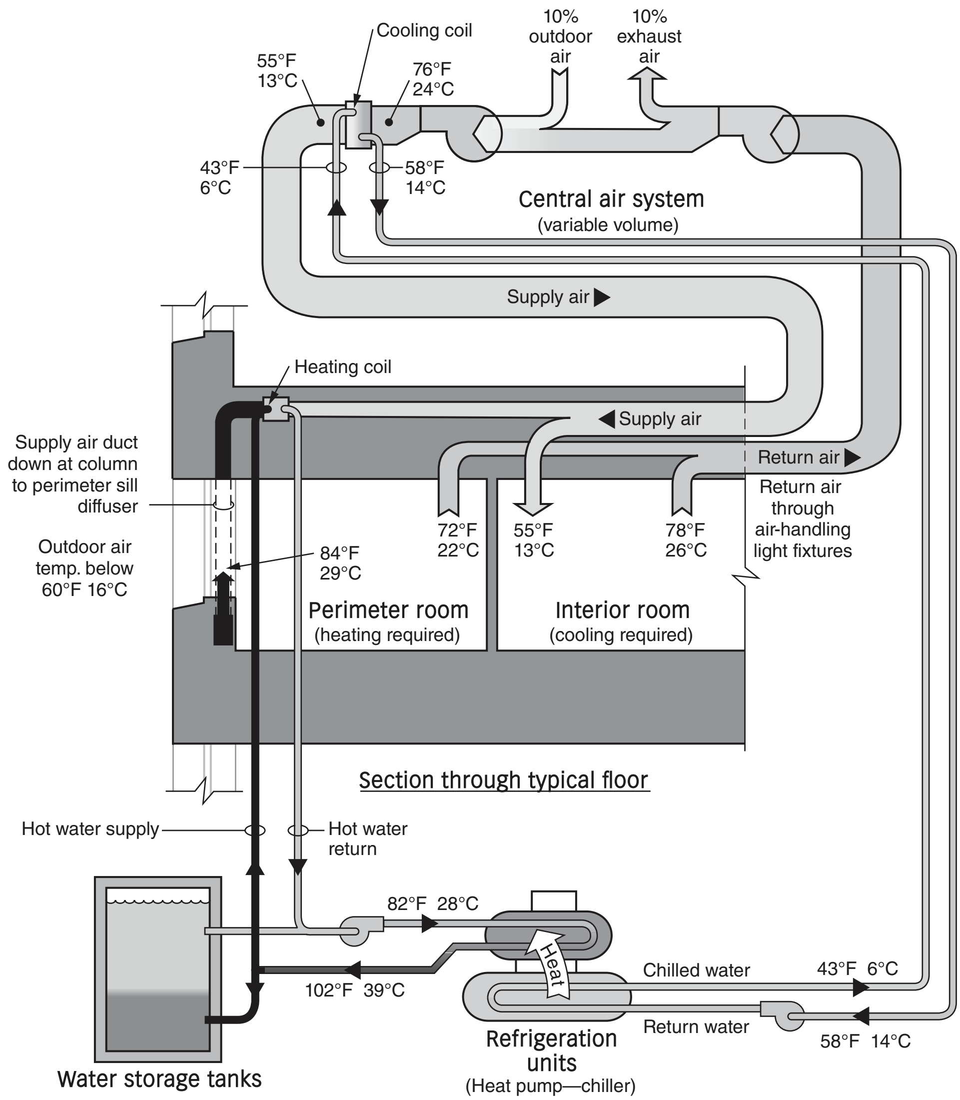
Relative to opening windows, the economizer cycle has several advantages: energy-optimizing automatic controls, filtering of the outdoor air, tempering of outdoor air to avoid unpleasant drafts, an orderly diffusion of outdoor air throughout a building (even locations distant from windows), and the opportunity for noise control. Its disadvantages are the loss of personal control that windows offer and thus loss of awareness of exterior–interior interactions.

Economizer cycles are available as an option on most direct expansion (DX) air-handling units (such as packaged rooftop units) and are typically installed in large-building central air supply systems. Buildings with high internal gains (internal load dominated) are particularly good targets for economizer cycles because they need cooling even when the outdoor temperature is chilly. Economizer cycles lend themselves readily to a cooling strategy of night ventilation of thermally massive structures because they have a built-in option for 100% outdoor air.

(c) Energy Storage

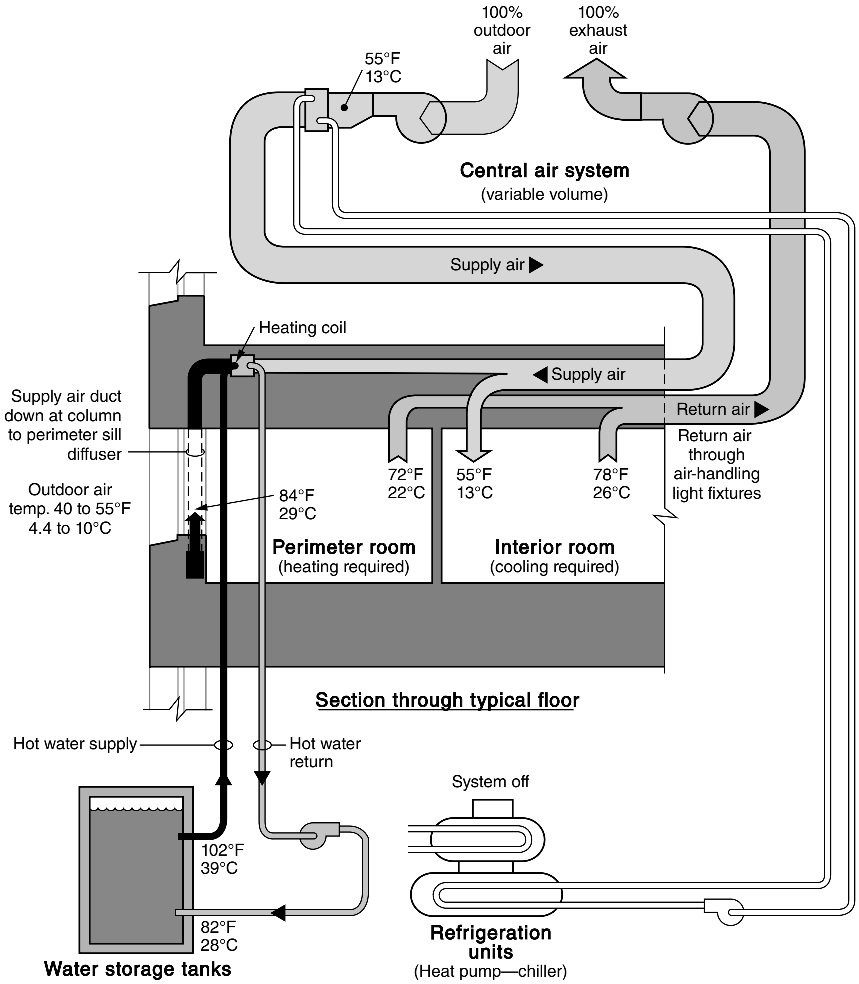
We commonly experience daily changes from warmer to colder. Central heat storage equipment in large buildings can take advantage of this cycle to increase operating efficiency, reduce resource consumption, and significantly reduce electricity demand charges. Some electric utilities offer incentives to install thermal storage in order to reduce the peak load strain on their generating facilities.

Water storage tanks, as shown in Fig. 12.125, are a common approach to thermal storage. On a typical winter day, the total internal heat generated by a large building can be somewhat greater than its total need for heating in the perimeter zones. Instead of being thrown away in exhaust air, this

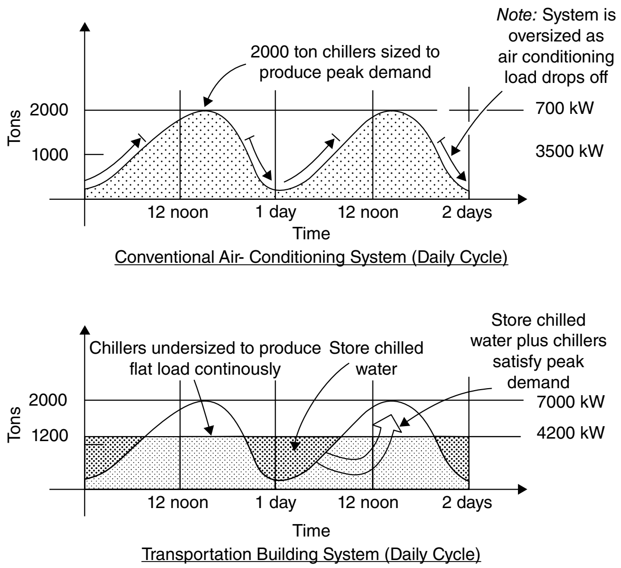


(*a*)

Fig. 12.125 *Water tank heat storage. The 870,000-ft² (80,825-m²) transportation office building (Park Plaza, Boston), population 2000, uses a three-compartment insulated concrete tank storing 750,000 gal (2,838,990 L) of water. (a) At an outdoor air temperature of 40 to 50°F (4.4 to 10°C), surplus internal heat is stored in the tanks rather than rejected in the exhaust air. (b) By the time the outdoor air is about 50°F (10°C), the tanks are fully charged; up to an outdoor temperature of 60°F (15.5°C), the economizer cycle provides energy-conserving cooling. (c) At about 60°F (15.5°C) chillers must operate, but working all night when the outdoor air is cooler enables them to work less by day. Their nightly production is stored as cold water, available to help with the following day's peak. Smaller machines and more efficient operation are the result. (Courtesy of Shooshanian Engineering Associates, Inc.)*



(*b*)



Note: Charging of storage tanks with cold water during off hours provides added cooling media for peak air-conditioning needs.

(*c*)

Fig. 12.125 *(Continued)*

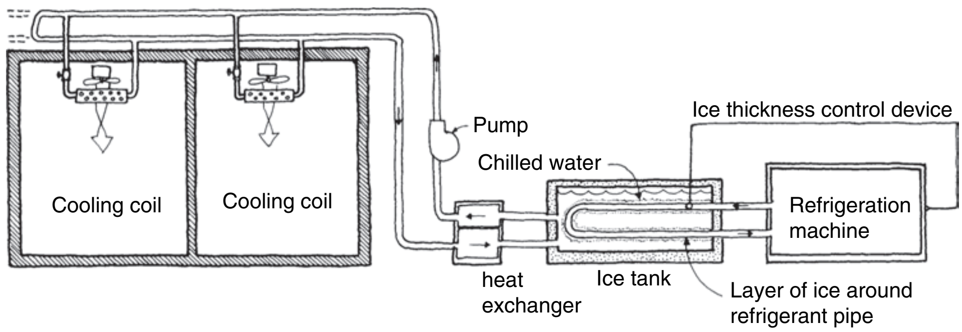


Fig. 12.126 *Ice tank heat storage. Chilled water (supplied by a refrigeration machine) in an ice tank forms a layer of ice around the refrigerant pipe. As chilled water at about 35°F (1.7°C) is removed from the tank, it enters a heat exchanger so that its temperature is closer to 45°F (7.2°C) for distribution to cooling coils throughout the building.*

surplus heat can be captured and stored in large water tanks, from which it can be withdrawn and used on cold winter nights and weekends. In the summer, chillers can work at night, when efficiency is higher because cool outdoor air helps the refrigeration cycle more easily reject its heat. Storing the coolth thus produced means that less work needs to be done by chillers during the next day's peak load time, when electric rates are highest and operating efficiency is lowest.

- Design guidelines for water storage are 0.5 to 1 gal/ft^2 (20 to 40 L/m^2) of conditioned space. Large, heavy tanks are frequently located in basements or underground parking facilities. Water tanks require that additional floor space be devoted to equipment, although they may allow somewhat smaller chillers to be installed. They may also contribute to lower fire insurance premiums because considerable water is stored and ready to use.
- *Ice storage tanks*, as shown in Fig. 12.126, are another thermal storage approach. Because ice storage takes advantage of the latent heat of fusion (143.5 Btu/lb of water at 32°F [334 kJ/kg at 0°C)]), such units can store far more energy in a given-size tank than can water. Design guidelines for ice storage are 0.13 to 0.25 gal/ft^2 (5 to 10 L/m^2) of conditioned space. A comparison of the relative sizes of storage tanks needed for an 18-story office building is shown in Table 12.12. With ice storage there is less undesired mixing of hot and cold water within the storage tank.

TABLE 12.12 Cooling Storage Comparison

Assume an eighteen-story office building: 375,000 gross ft^2 (34,840 m^2), 800 tons (2800 kW) peak load, 6250 ton-h/day (21,908 kWh/day) at design, 75 million Btu (21,900 kWh) storage needed.

	Water Storage	Ice Storage
Btu/lb[a] (kJ/kg)	15 (34.9)	164 (381.5)
Pounds storage	5,000,000	457,000
(kilograms)	(2,267,960)	(207,290)
Gallons	599,500	54,800
(liters)	(2,269,300)	(207,435)
Storage efficiency	0.90	1.0
Percent ice		66%
Net gallons	666,000	83,030
(liters)	(252,100)	(314,295)
Cubic feet	89,046	11,101
(cubic meters)	(2522)	(314)
Floor area of tank,		
approx. 8 ft deep	80 by 150 ft	30 by 50 ft
(2.5 m deep)	(24 by 46 m)	(9 by 15 m)
Storage ratio, water to ice	8 : 1	

Source: Reprinted by permission from *Specifying Engineer*, January 1983. SI conversions added by the authors of this book.

[a]Btu/lb based on Δt = 15F° for water storage and on Δt = 20.5F° in the melted ice water (added to 143.5 Btu/lb at fusion).

Ice can be produced in several ways. A common method is to form ice as a layer around a pipe that carries refrigerant in a closed circuit through the tank. Control of the thickness of this layer is important, because if too little ice is made at night, too little cooling will be available the following day. In another method, ice is formed and thawed by circulating a brine through coils in cylindrical water tanks. Other methods form ice on plates, then harvest it in an insulated bin.

The Iowa Public Service Building (Fig. 12.127) uses ice storage in six tanks that occupy about half of the floor space in the ground floor mechanical room. This installation serves a five-story, 167,000-ft^2 (15,515-m^2) utility office building that utilizes solar collectors supplemented by small backup boilers. Six ice-making machines serve a 75,000-gal (283,900-L) ice storage pit with 90 million Btu (26,355 kWh) capacity. Winter heat exchange opportunities include reject heat from the ice-making machines, heat from the centralized toilet exhaust air, and heat from return air taken through luminaires. Solar collectors on the roof preheat the ventilation air, which is fed into the ceiling plenum at each floor. Fan-coil units then draw from this fresh air supply.

Water and ice storage tanks are sometimes located at the top of a building, especially when related mechanical equipment is there also. Despite the weight of such tanks, they can become a structural advantage. The tuned mass damper method of reducing lateral vibration (or sway) in high-rise buildings utilizes a heavy, moving mass at the top; when the building begins to sway, the mass is moved in the opposite direction. In the Crystal Tower in Osaka, Japan, this mass is provided by ice storage tanks. This 515-ft (157-m), 37-story building has an ice thermal storage volume of 25,400 ft^3 (720 m^3) divided into nine tanks. Six of the ice storage tanks provide the movable structural mass, suspended from roof girders, weighing 540 tons (489,880 kg), including steel framing. The chiller and condenser are also in the equipment penthouse.

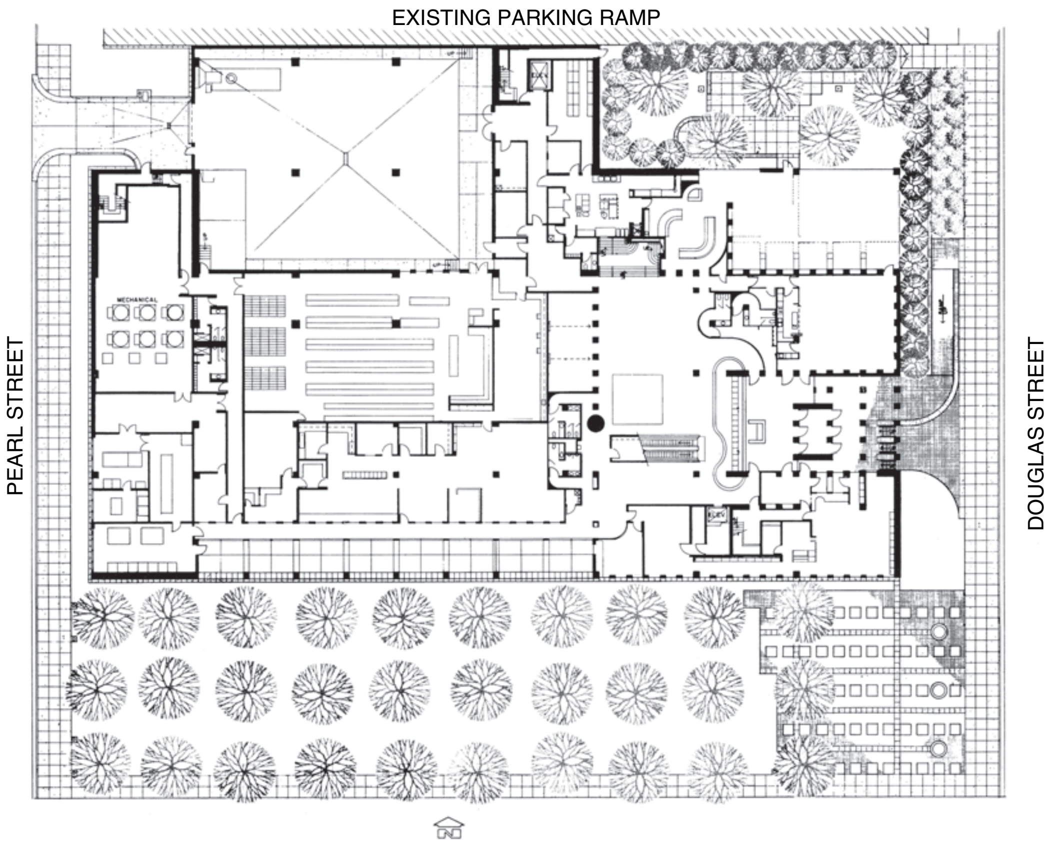


Fig. 12.127 *The ground floor of the Iowa Public Service offices (Sioux City) contains six ice machines within the mechanical space adjacent to the loading dock. (Courtesy of Rossetti Associates and Foss, Engelstad, Heil Associates, joint venture architects.)*

A multi-pronged approach to heat storage is illustrated in the building featured in Fig. 12.128. In England, the Hyndburn Borough Council decided that their new headquarters building should set an example as a "zero energy" building: That is, over a typical year, it should generate as much energy as it imports. The 38,750-ft^2 (3600-m^2) building is elongated east–west and boasts an ambitious section that combines daylighting, photovoltaics (PV), a well-insulated skin, and even rainwater collection to use for flushing toilets. Windpower adds to electricity generation. Summer cooling is by ventilation (assisted by night ventilation of mass) through a raised "Termodeck" system. This is a prefabricated hollow-core slab through which cool night air circulates, storing coolth to assist the next day's hottest hours. The raised floor then provides a distribution plenum, with a design rate of 4 air changes per hour (ACH).

(*a*)

Fig. 12.128 *The Hyndburn Borough Council headquarters faces south toward a reservoir (a) that provides an evaporatively cooled microclimate and also acts as a heat source/sink for a water–water heat pump. (b) As suggested in the diagrammatic section, daylighting, passive solar heating, PVs, and a well-insulated shell are featured. Termodeck is a precast hollow-core slab that stores coolth on summer nights and precools ventilation air. The supply air rises from the plenum created by the raised floor. (Courtesy of Jestico + Whiles + Associates, architects, London.)*

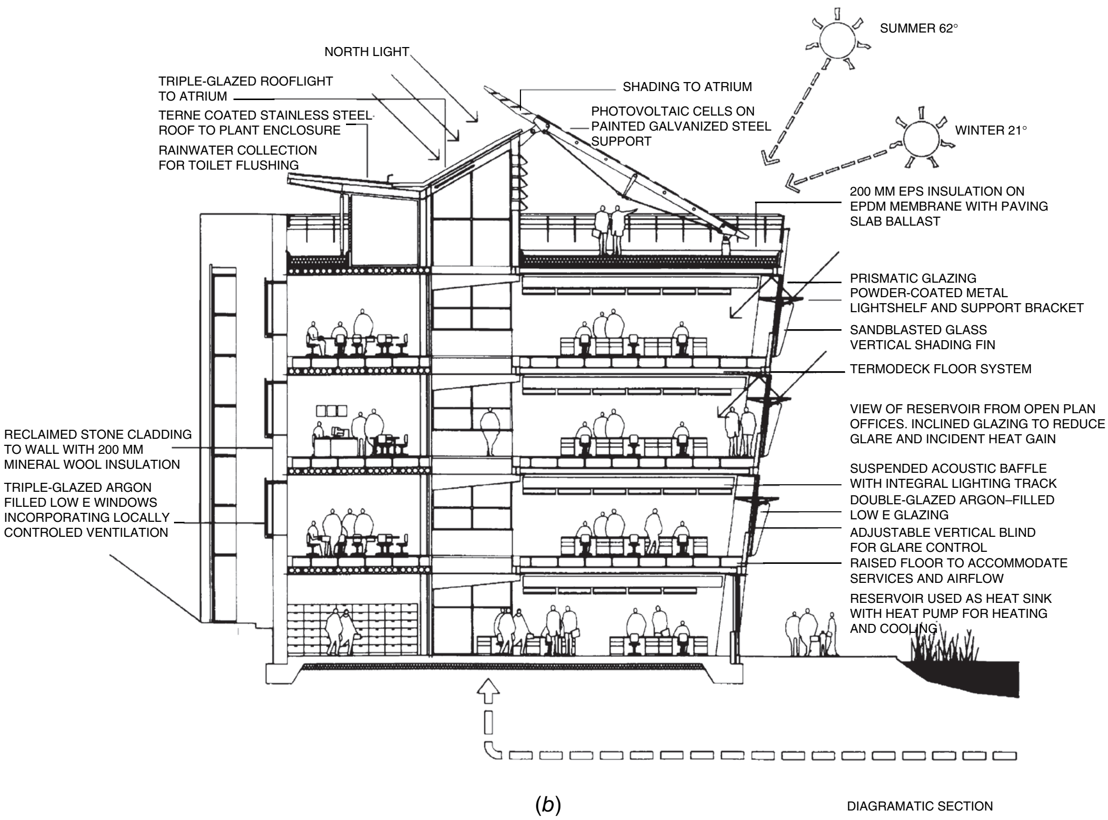


Fig. 12.128 *(Continued)*

For more extreme future summer cooling, but now mostly for winter heating (beyond that provided by passive solar heating), an adjacent reservoir acts as a thermal sink. A "lake closed source heat pump" will serve the mechanical ventilation system. The lake is south of the building, providing some local evaporative cooling in summer and inviting a very climate-oriented south façade, behind which are open-office areas. The north façade faces the city and is more traditionally institutional in character, as are the individual offices behind it.

(d) Cogeneration

Electricity has repeatedly been called a high-quality resource in reference to the many, many tasks that it can be applied to—but also with regard to the high temperatures needed to produce electricity by conventional (fossil-fuel) means and to the large amount of waste heat (often twice the heat value of electricity) produced in the process. Cogeneration (also called total energy) represents an attempt to recover some of the otherwise wasted low-temperature heat that accompanies the generation of electricity by steam turbines. Industrial cogeneration facilities are especially cost-effective in the pulp and paper, petroleum, and chemical industries. Building-scale cogeneration is a less obvious energy bargain.

Where conditions are favorable, electricity for power and lighting can be generated economically by a system that also supplies the building with heating in winter and cooling in summer. Such a system utilizes a fuel such as gas or oil and is often supplemental to the local electric utility company. Although first costs are greater than for more conventional energy systems, the savings in annual operating costs can sometimes pay for the installation cost in a reasonable time. Operational savings continue thereafter. This approach was developed largely in the 1960s and is used in hundreds of commercial and industrial buildings and in many schools. Cogeneration is particularly attractive for district heating/cooling plants.

Before 1900 nearly all large buildings and groups of buildings were supplied with direct-current electricity generated on or near the premises. The motive power was usually a steam-driven reciprocating engine with belt connections to direct-current generators. Direct current cannot be transformed to different voltages and must be generated and distributed at the voltage used in the building. At these relatively low voltages, power loss in the distribution system is great, and distance adds greatly to the loss. This tended to favor local generation of power.

With the development and use of alternating-current machines, utility companies were able to establish central power stations from which electricity at high voltage could be transmitted great distances to the users. It was transformed down to domestic voltages on the building site (or nearby). Because, at high voltage, power losses are fairly low, this system became universal. During the 1920s and 1930s, owners removed their private power generators and accepted utility service, with its savings in operating expense.

For cogeneration to be successful, there should be a reasonably steady demand for the power being generated and also for the heat being recovered. Lighting, computers, business machines, and other devices can create nearly constant demand for power throughout the year. Similarly, the exhaust heat recovery from the engines or turbines that power the generators is in demand for either heating or absorption refrigeration during most of the year.

Figure 12.129 shows two principal approaches to total energy. In both systems—one using a turbine and the other a reciprocating engine to operate the electric power generator—heat is reclaimed to produce steam or hot water. The steam or hot water is then used for heating or, via an absorption chiller, for cooling. When a turbine is used, the fuels are natural gas or fuel oil. The heat is recovered by passing the hot turbine exhaust through a waste heat boiler to produce steam. Fuel for a reciprocating engine is natural gas or diesel fuel. Both the jacket cooling water and the hot engine exhaust are passed through heat exchangers that utilize the heat to produce steam or hot water for heating or cooling. In both systems, an auxiliary boiler, fired directly by gas or oil, stands ready to help maintain a balance in the system.

The Harbortown apartment and townhouse complex in Detroit, Michigan, utilizes a year-round natural-gas-fired primary energy and cogeneration/waste recovery system (Fig. 12.130). Each apartment has one or two stackable, upright fan-coil units using either chilled or heated water. This water is provided by two direct-fired chiller–boilers: Each incorporates a natural gas boiler and a two-stage absorption chiller in the same unit, taking less space in the mechanical room. The natural-gas-driven cogeneration electric plant serves rather constant loads such as corridor and outdoor lighting. The waste heat from the generator is passed to a storage tank, where it preheats domestic hot water; this meets about 87% of the hot water energy usage.

(e) Fuel Cells

A fuel cell generates direct-current electricity by converting the *chemical energy* of hydrogen and oxygen into electricity and heat. Because no combustion is involved, nitrogen oxides and carbon monoxide are nearly eliminated as pollutants. For a building fuel cell power plant, several components are added. First, a fuel processor (or fuel reformer) to prepare a hydrogen-rich stream of fuel, then the fuel cell stack, then a power conditioner (or inverter) to convert the direct-current fuel cell output to alternating current.

Fuel cells are not, by themselves, that much more efficient than combustion processes; they are about 40% efficient for power production. When combined with a way to use the 60% waste heat, however, they climb toward 90% efficiency, with very few harmful emissions.

Hydrogen is the ultimate fuel; already hydrogen-rich, it needs no processor and produces the least environmental impacts from the fuel cell. Other hydrocarbon fuels, however, also can feed fuel cells: natural gas (most common for building-scale fuel cell power plants), propane, methanol, and, with additional pretreatment, methane from landfills and anaerobic digester gas from sewage treatment plants. Even with these less hydrogen-rich fuels, the emissions from fuel cells are well below those of

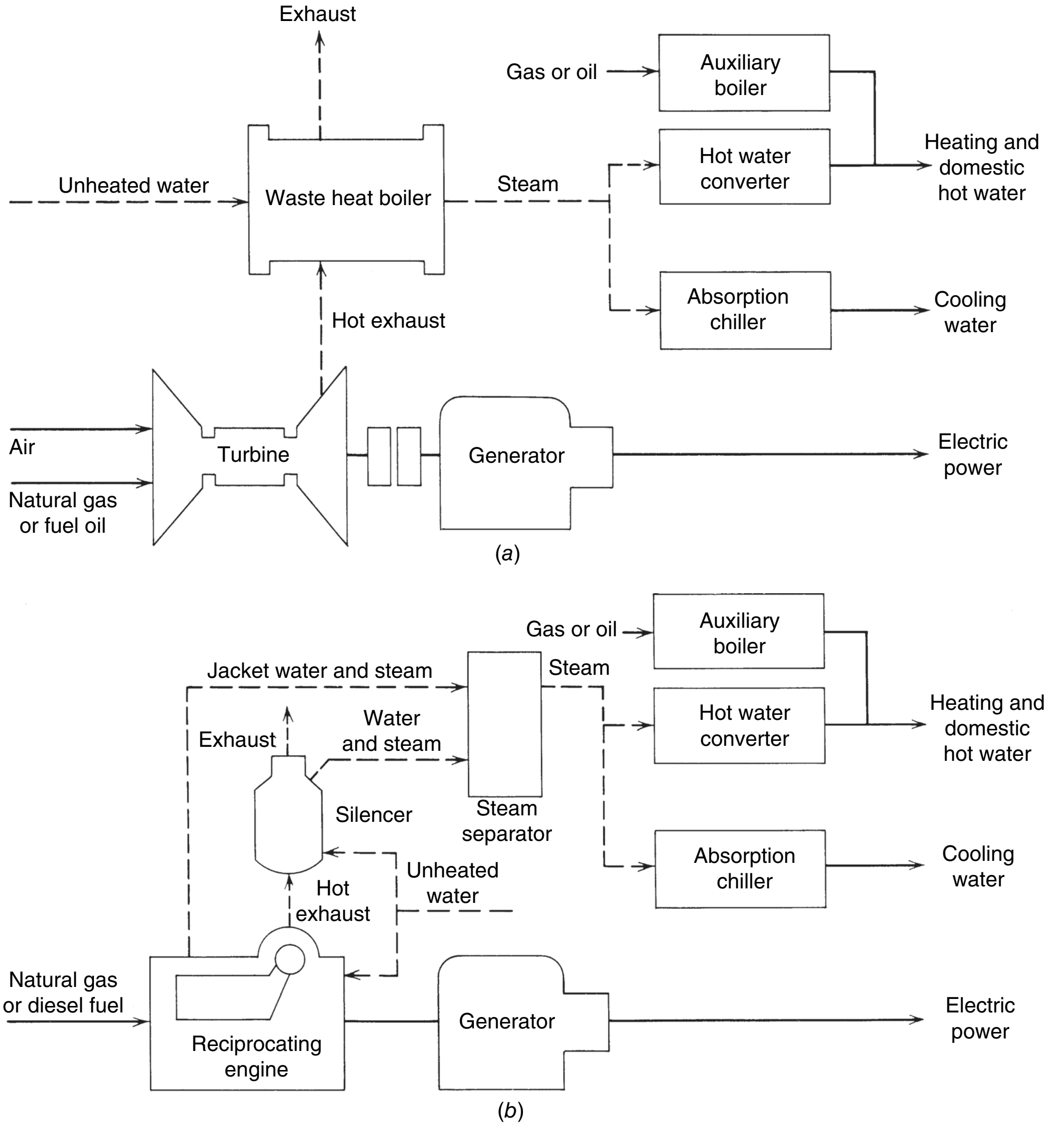


Fig. 12.129 *Cogeneration (total energy) systems. (a) Using a turbine. (b) Using a reciprocating engine. (Reprinted by permission from* Total Energy, *Educational Facilities Laboratories.)*

combustion processes; the fuel processor emits carbon dioxide and a trace of carbon monoxide.

Proton-exchange membrane (PEM) fuel cells (Fig. 12.131) are promising for transportation when zero-emission vehicles are the objective and hydrogen is available as a fuel. This process has building applications as well. It works at a temperature below the boiling point of water. Relative to other fuel cell types, PEM has a smaller size, lighter weight, and lower noise levels. The PEM fuel cell stack involves several subsystems, typically including water purifiers and pumps, air compressors, and heat rejection components (coolant pumps and a radiator). This complicates performance at subfreezing temperatures and adds maintenance requirements. But the smaller size promises potential for small-building applications.

The phosphoric acid fuel cell power plant (Fig. 12.132) is at work in (or outside) a number of buildings and municipalities around the world. The ONSI Corporation's 200-kW fuel cell power plant measures 10 ft × 18 ft, is 10 ft high (3 m × 5.5 m,

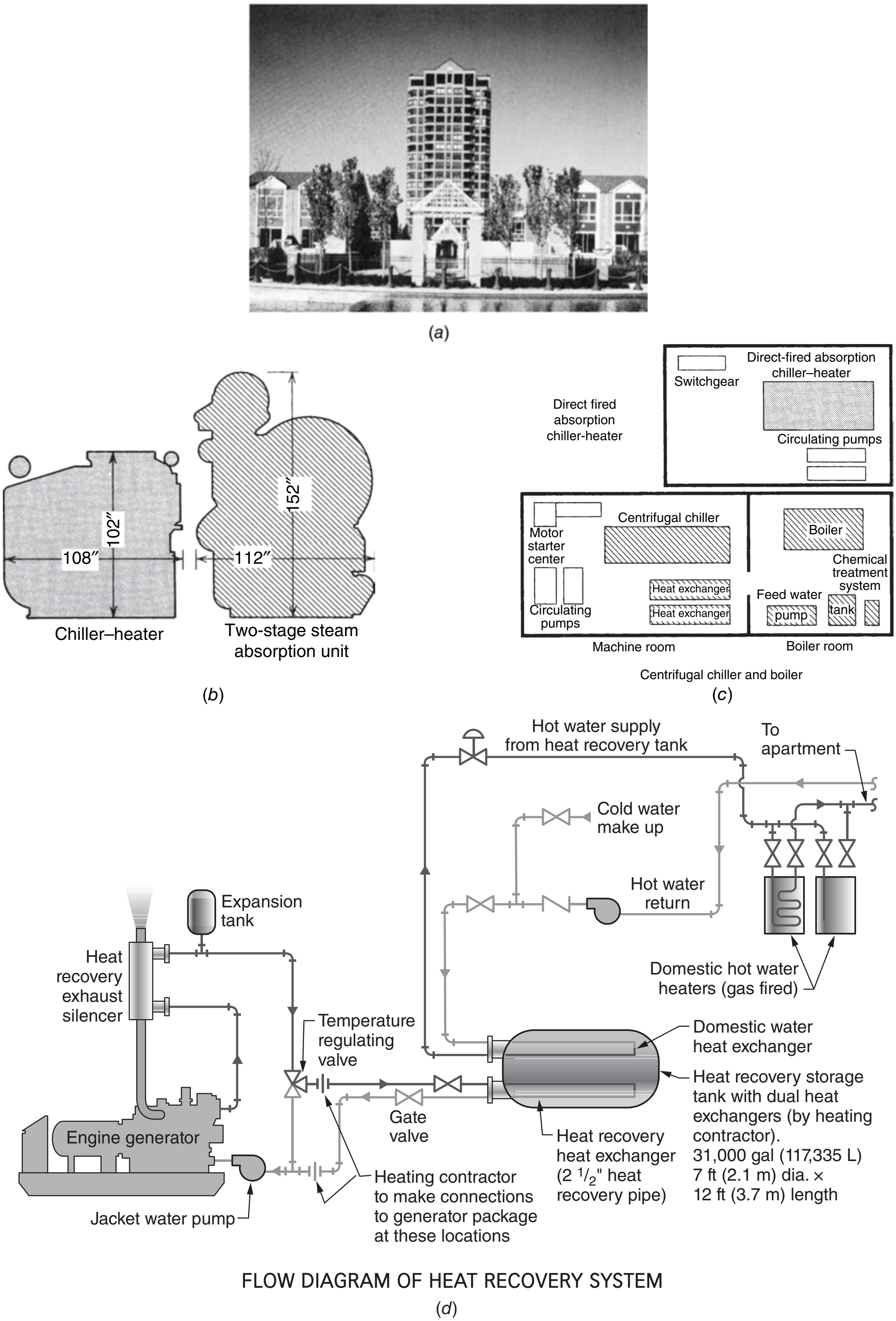


Fig. 12.130 *Harbortown is a 120,000-ft² (11,150-m²) apartment and townhouse complex (a) in Detroit that uses natural gas as a primary fuel year-round. (Photo © 1989, William Kildow.) Chiller–heaters (Hitachi) combine a boiler and a two-stage absorption chiller in one compact unit. (b) Comparison of headspace and (c) floor space required by chiller–heaters versus conventional units of similar capacities. (d) Cogeneration plant sends waste heat to preheat domestic hot water. (Courtesy of Skidmore, Owings & Merrill, Architects-Engineers, Chicago.)*

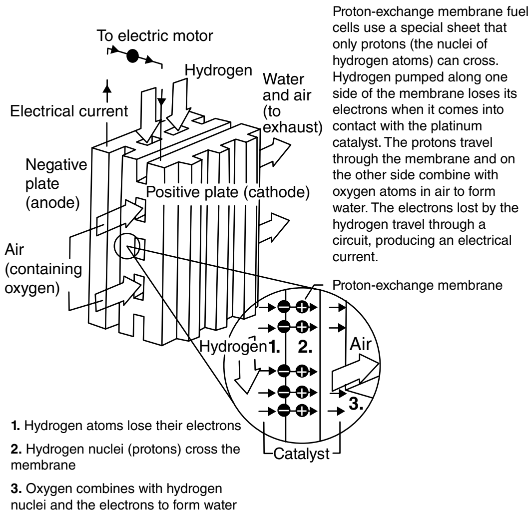


Fig. 12.131 *Schematic diagram of a proton-exchange membrane (PEM) fuel cell with a description of its operation. (Courtesy of* Nucleus, *Fall 1994; © Union of Concerned Scientists, Cambridge, MA.)*

3 m high), weighs 40,000 lb (18,144 kg), and needs a clearance of 8 ft (2.5 m) around the module for maintenance. It also needs a cooling module (or use of a building cooling tower) for discharge of heat in excess of that recovered for building use. The acid electrolyte in the fuel cell stack works at about 390°F (200°C). At its rated power, it also produces 700,000 Btu/h (205 kW) to heat a water stream to 140°F (60°C). The rated sound level is 62 dBA at 30 ft (9 m) from the module.

The Durst Organization's high-rise office building at 4 Times Square in New York City (Fig. 12.133) is a demonstration of several interesting energy-efficiency strategies: PV cells integral to the façade, direct-fired (natural gas) absorption chillers, increased outdoor air for IAQ (maybe not so energy efficient), a dedicated exhaust air shaft (for polluting activities), and waste chutes to facilitate recycling, among others. It also utilizes two 200-kW fuel cell power packages fed by natural gas. The electricity is about 80% destined for external lighting by night; huge electrical signs are a prominent part of the Times Square façades. By day, about 80% of the power goes to the building's base load. The hot water will be used in winter for perimeter heating. In summer, the water is wasted. Although there was hope that one of the absorption chillers could be fed by this water, a variety of considerations precluded this: The fuel cells are located on the fourth floor (accessible to maintenance and close to the huge signs), whereas the chillers are located in the penthouse.

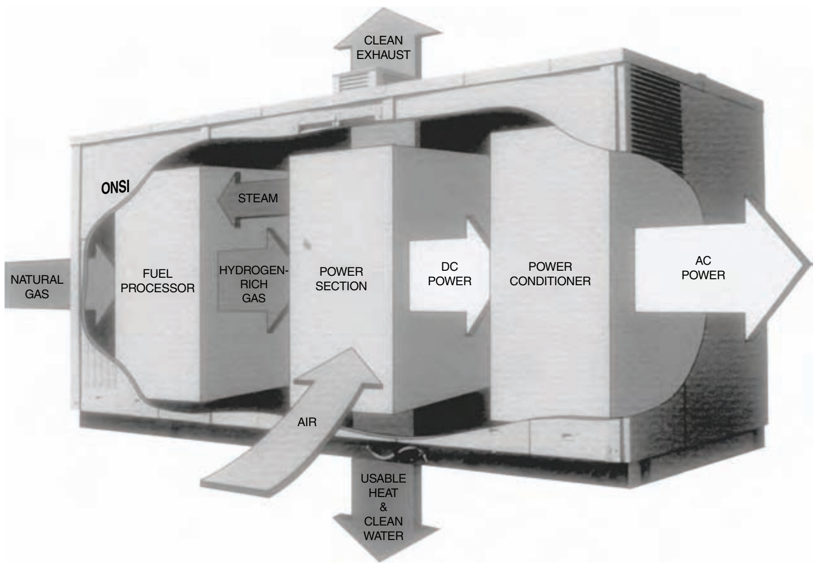


Fig. 12.132 *A fuel cell power plant using natural gas (or other hydrocarbon fuel). The fuel processor (reformer) converts the natural gas to a hydrogen-rich stream that enters the fuel cell power section (or stack). The output is electricity (DC), water, carbon dioxide, and considerable heat. Some heat is used by the fuel processor and some is rejected, but most is usable in a building. A power conditioner (inverter) converts DC to AC power. (Courtesy of ONSI Corporation.)*

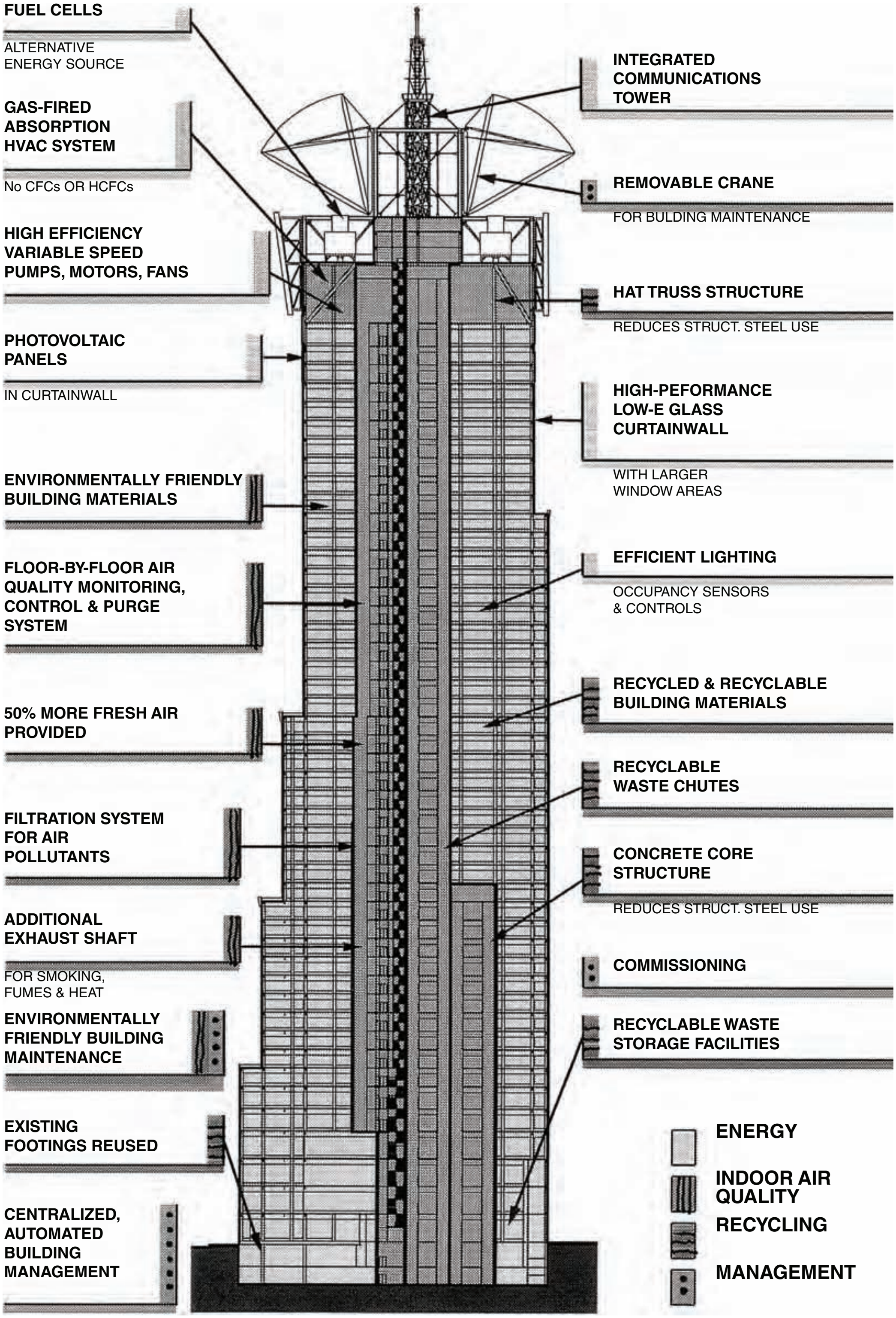
The 200-kW fuel cell in Fig. 12.132 is usually fed by natural gas, but other examples include hydrogen fuel (Hamburg, Germany: electricity to the grid, hot water to heat an apartment building), anaerobic digester gas (Yonkers, New York: wastewater treatment plant; electricity and hot water used within the facility), and landfill gas (Groton, Connecticut: closed landfill; electricity to the grid). Plentiful hot water is a by-product of the fuel cell; it seems that finding a viable year-round use for this water is often a problem.

The HVAC systems in the Solaire and Verdesian apartments in New York City (Fig. 12.134) bring fresh air into individual apartments and exceeded the New York City energy-efficiency standards by more than 35% by using variable air speed fans, gas-fired absorption chillers and heaters, occupancy sensors, and optimized indoor air quality,

(*a*)

(*b*)

Fig. 12.133 *The 48-story office building at 4 Times Square, New York City (a), (b), (c). Many environmentally friendly features are included, such as façade-integrated PV and two fuel cell power plants like those shown in Fig. 12.132. Fed by natural gas, the fuel cells are expected to work without maintenance interruptions for up to 5 years and provide considerable hot water as well as electricity. (The fuel cells are actually installed at the fourth-floor level rather than at the penthouse.) ([a] Licensed under Creative Commons Public License; [b] Photo © Gabrielle de Briey, used with permission; [c] Drawings courtesy of Fox and Fowle, Architects, P.C., New York; Consentini Associates, Mechanical Engineers; the Durst Organization, Developer.)*



(c)

Fig. 12.133 (Continued)

Fig. 12.134 *Clarke Pelli Clarke Architects designed The Solaire (left), the first LEED Gold multifamily high-rise, in 2003 and The Verdesian (right), the first LEED Platinum multifamily high-rise, in 2006. (© Jeff Goldberg/Esto and Clarke Pelli Clarke Architects; used with permission.)*

using fresh and filtered air to all units and little or no volatile organic compounds on the interior finishes. The base system for both buildings is a gas absorption chiller system with a four-pipe fan-coil for delivery. The difference between the two buildings is that the Verdesian added a micro turbine for domestic hot water, and the ventilation rates were reduced as a test case for the New York City Department of Building.

The Verdesian is linked to the Solaire's blackwater treatment plant, which recycles water from bathrooms and kitchens for use in toilets and provides make-up water for the HVAC system cooling tower. The building also harvests rainwater and can store 10,000 gallons (37,854 L) of recycled water for irrigation of the rooftop garden.

12.21 CASE STUDY—ACTIVE CLIMATE CONTROL SYSTEMS

The Mercy Corps Global Headquarters Building, Portland, Oregon, USA

PROJECT BASICS:

- Location: Portland, Oregon, USA
- Latitude: 45.5°N, longitude: 122.6°W
- Heating degree days: 4695 base 65°F (2608 base 18.3°C); cooling degree days: 551 base 65°F (305 base 10°C); annual precipitation: 37.1 in. (940 mm)
- Building type: Addition to and renovation of Packer-Scott Building; commercial office space
- Size: 82,800 ft^2 (7618 m^2) gross floor area
- Completed: September 2009
- Client: Mercy Corps
- Design team: THA Architecture, Walker Macy (landscape), ABHT Structural Engineers, Glumac (HVAC), David Evans & Associates (civil), American Heating Inc. (HVAC contractor), Thermal Supply (HVAC distributor), Walsh Construction Company (contractor)

Background. Mercy Corps developed their global headquarters as a renovation of the existing Packer-Scott Building (built in 1892) with a new 40,000 ft^2 (3726 m^2) addition. The site, located in the economically depressed Old Town area, provided an opportunity to not only unite Mercy Corps headquarters staff but also provide a catalyst for positive change in the economically challenged neighborhood. Their new headquarters exemplifies the organization's sustainable, community-focused approach.

Fig. 12.135 *The east facade opens to the adjacent riverside park. (© Jeff Amram, THA Architecture; used with permission.)*

Fig. 12.136 *The historic Packer-Scott Building (built in 1892) offers important contextual and environmental control system cues such as punched window openings on the southern elevation. The new addition has a low window-to-wall ratio and helps to control solar gain in summer and heat loss in winter. (© Jeff Amram, THA Architecture; used with permission.)*

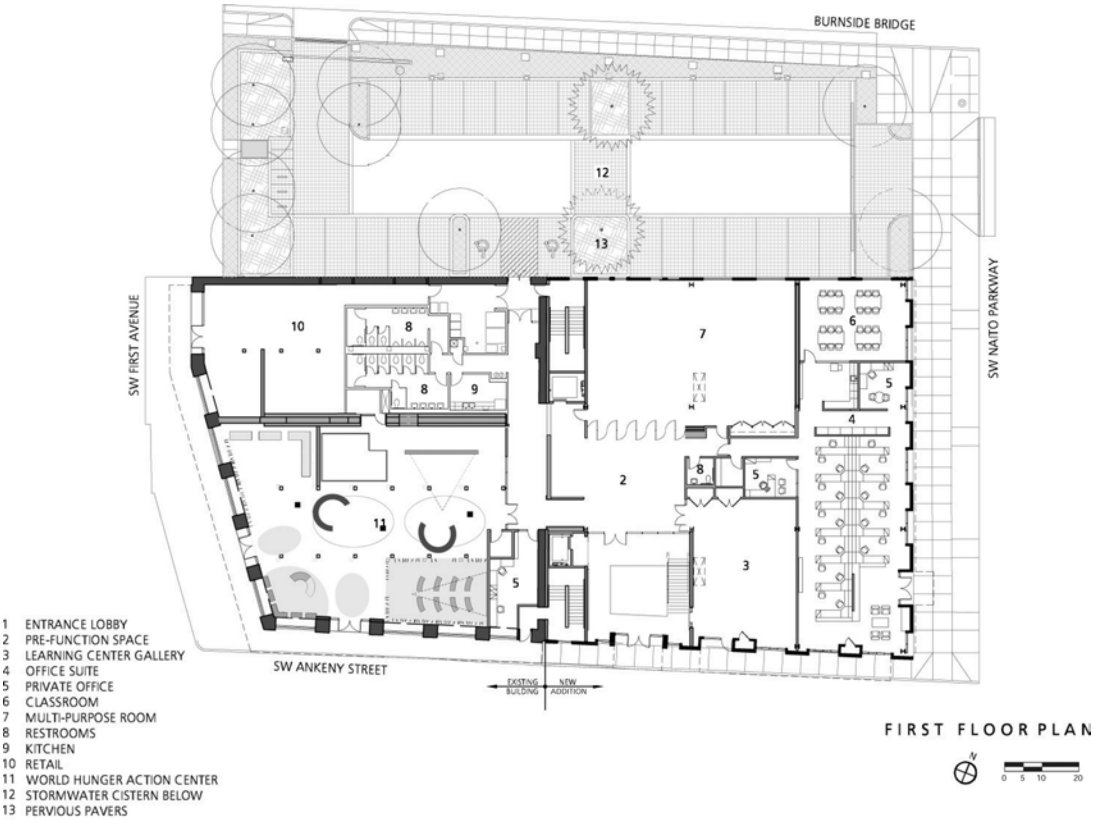


Fig. 12.137 *First-floor plan shows the entry lobby on SW First Street into the renovated Packer-Scott Building; the new addition on the right has an entry from Ankeny Street to a centralized circulation core to the upper floors. (© THA Architecture.)*

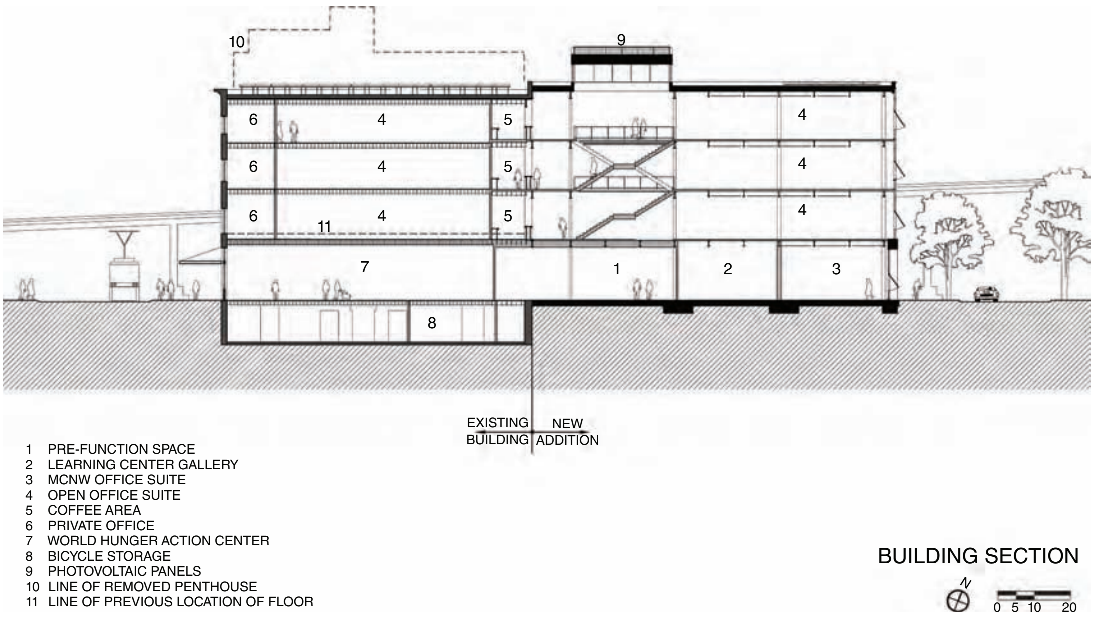


Fig. 12.138 *Section showing central circulation core between the second and third floors that allows for stack ventilation through a motorized monitor above. (© THA Architecture.)*

Fig. 12.139 *The daylit entry provides a pathway for stack ventilation from the entry up through the central stair core. (© Lara Swimmer, THA Architecture; used with permission.)*

Fig. 12.140 *Clerestory windows of the roof monitor above the central stairs are mechanically actuated by CO_2 sensors. (© Lara Swimmer, THA Architecture; used with permission.)*

Fig. 12.141 *Aerial view showing integration of technologies on the roof: eco-roof, racks ready for photovoltaics to later serve as shading for the eco-roof and energy experiments, and clerestories over atrium. (© Bruce Forster, THA Architecture; used with permission.)*

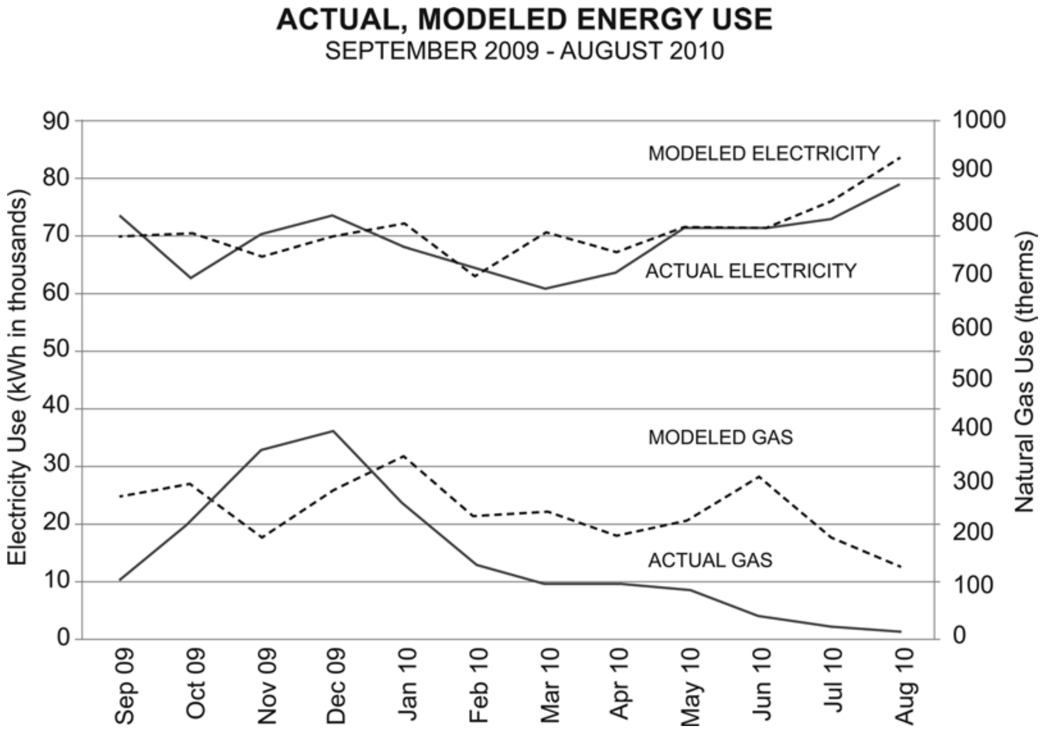


Fig. 12.142 *Modeled vs. actual energy use for one year. (© Glumac; redrawn with permission.)*

Mercy Corps' mission is to foster sustainable economic development through collaboration and self-empowerment. The headquarters also includes the Action Center on the ground floor—a window to the world—featuring interactive exhibits that educate visitors about the constantly changing nature of relief and development work and provide suggestions for concrete ways people can act now to help. Also on the ground floor, community education and meeting facilities further extend the headquarters' role within the community.

Context. Mercy Corps, a global humanitarian organization, is dedicated to building physical and human resources in communities that experience poverty, hunger, and war. The collaborative working culture of Mercy Corps synchronized with an integrated design process involving numerous workshops with the contractor, architect, engineers, and design consultants. The integrated design process was part of a critical set of steps leading to building a LEED Platinum building that required highly integrated HVAC, passive, electrical, and structural systems.

Design Criteria and Validation. LEED Platinum was targeted as a goal that would reflect the organization's commitment to sustainable development. Energy was the primary driver of design decisions, motivated by the goal of achieving all ten of the LEED Energy and Atmosphere credits. The motivation to reduce water consumption and adapt the Packer-Scott Building played a major role in determining design criteria and parameters for the new addition.

Design Approaches. From the early design phases, the team sought to implement sustainable design strategies. The reuse of the existing building minimized the need for new materials and carbon-intensive construction, and reflected Mercy Corps' values of resourcefulness and sensitivity to culture. An open floor plan helps support a collaborative office culture, while allowing for passive strategies such as daylighting and stack ventilation to achieve improved energy performance.

Design Features

HVAC. A heat-pump system with variable refrigerant flow was selected for heating and cooling because of its low initial cost, quietness, adaptability, and ability to provide the necessary thermal zones in the addition and in the renovation of the Packer-Scott Building. There are five VRF loops in the building.

The variable refrigerant flow system was critical to achieving energy performance goals. The layout of the heat exchange systems and the orientation of the building façades have a big impact on energy use. Due to the circulation layout and the nature of the building (an addition onto a renovation), the HVAC system was set up to allow for radiant gains in the south-facing spaces to be transferred to the north side of the building through the VRF loops.

Ventilation. A dedicated outdoor air system (DOAS) works in parallel with the variable refrigerant flow (VRF) heat pumps. Passive cooling via ventilation is available when conditions are appropriate. The passive ventilation system is coordinated with the active DOAS system. Pathways for stack ventilation and cross-ventilation are accommodated by an open vertical circulation core and by operable windows on the north and south enclosures. Passive cooling in the building has both automatic and manual aspects. It is mechanically actuated and user-operated, allowing for convenience and occupant control. A CO_2 sensor automatically opens the windows of the roof monitor to provide fresh air when needed, and occupants can control their own comfort and air quality through operable windows.

The ventilation system allows for a simplified sequence of control for the morning warmup. Prior to building occupancy and VRF system startup, the DOAS is converted to a recirculation air system and uses low-cost natural gas to warm up the building from the overnight setback temperatures.

In the same manner, a nighttime flush sequence is implemented during the summer. The design team chose parallel DOAS systems over series DOAS systems for the ease of sequencing.

Occupant Control. Operable windows on all sides of the building allow occupants to open windows. In addition, occupants have a weather data dashboard on their computers to monitor outside conditions—with the idea of improving both comfort and energy performance in the building through informed decision making.

Daylighting. The east–west building massing optimizes solar access and daylighting of office space. The new addition maintains a similar glazing-to-opaque-wall ratio as the existing historic building's punched window strategy. On the south side, trees provide a first level of solar control that provides light in the winter and shade in the summer. Photovoltaic integrated glass sunscreens shade southern-exposed glass and provide carbon-free power. The glazing strategy for the building includes: (a) a fairly low window-to-wall area ratio, (2) reasonably good window U-factors, (3) reasonably low solar heat gain coefficients, and (4) upgrading window performance in the retrofit portion of the building.

Envelope. The upgrades included adding continuous interior insulation of R-10, brick repair, and repointing of the existing masonry enclosure to improve its performance as an air barrier. The wall assembly design in turn drove the window improvements, which included upgrading windows' U-factors.

The enclosure assembly was designed to limit thermal bridging, provide a good air barrier system, and control solar radiation through windows. To limit heat transfer through the structure, slab, ceiling, floor plates, and steel frame, all the thermal control layers of the assembly are located on the outside of the structure.

Water. Water conservation at the Mercy Corps includes the reduction of water use by filtering and retaining storm water on site. Low-flow toilets and faucets reduce water consumption by 44% from typical potable water use, while landscaping is designed with drought-resistant native plants to eliminate the need for irrigation. Storm water is filtered by a 38,000 ft^2 (3530 m^2) vegetated roof that also reduces the air temperature around the building, and delays the flow of rainwater into the Willamette River.

Energy. The Mercy Corps building employs a range of passive strategies that run in parallel with a VRF HVAC system to reduce energy loads in the building. The building owner plans to install solar panels on the roof with the intent to further reduce energy dependence, in anticipation of reaching net zero by 2030. As the project progressed, the DOE2-based eQUEST energy model software analysis was updated as the team of architects, engineers, and contractors fine-tuned the performance of the envelope, window placement, sizing, and operation and electric lighting controls. The building is performing well. There is less natural gas usage than anticipated, suggesting that the ventilation strategy in the winter (using the dedicated outdoor air system for morning startup) is working.

Post-Occupancy Validation Methods. After a year of operation, post-occupancy energy analysis revealed that the measured data were consistent with modeled data. Actual gas use is significantly lower than predicted, a result that can likely be attributed to the highly adaptable ventilation rates within the building. This finding further strengthens the energy-saving value of a DOAS.

Performance Data:

- Achieved LEED Platinum rating
- Actual EUI: 36,000 Btu/ft^2 (408,960 kJ/m^2) per year
  - Electricity (from grid): 34,000 Btu/ft^2 (386,240 kJ/m^2)
  - Natural gas: 2000 Btu/ft^2 (22,720 kJ/m^2)
- Annual actual energy costs: \$0.98/ft^2 (\$10.55/m^2)
- Percent reduction from national average EUI for building type: 53%
- Lighting power density: 0.74 W/ft^2 (7.98 W/m^2)
- Waste: 87% of the existing historic Packer-Scott Building was re-used; 95% of waste was diverted from the landfill through recycling or reuse
- More than 10% of the new materials used were extracted, processed, and manufactured regionally
- Water: Annual water use is reduced by 44%

Awards:

2009 LEED-NC v2.2 Platinum

2011 "Good Design is Good Business Award"

2011 National Housing & Rehabilitation Association J. Timothy Anderson ("Timmy") Award for Best Historic Rehabilitation Involving New Construction

2012 AIA Committee on the Environment "Top Ten Green Projects"

FURTHER INFORMATION

Dorn, Charles and Rob Schnare. March 2013. "Building With a Mission." *High Performance Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA: http://www.hpbmagazine.org/case-studies/office-institutional/mercy-corps–world-headquarters-portland-or

The DOE2 e-Quest Mercy Corps Energy Report for the AIA COTE Top Ten: http://www.aiatopten.org/node/51

Mercy Corps: http://www.mercycorps.org/

THA Architecture: http://thaarchitecture.com/mercy-corps-global-headquarters

Carinci, Justin. 2009. "A Blend of Old and New at Mercy Corps' New Headquarters." *Daily Journal of Commerce*, August: www.mercycorps.org/press-room/clips/blend-old-and-new-mercy-corps%E2%80%99-new-headquarters

Kolleeny, Jane. 2011. "A Catalyst for Change: The New Headquarters of Mercy Corps Accomplished Multiple Goals For Its Employees, For The Local Community, and For The Environment." *GreenSource*, May: http://greensource.construction.com/green_building_projects/2011/1105_Mercy_Corps_Global_Headquarters.asp

References and Resources

Allen, E. 1989. *The Architect's Studio Companion*. John Wiley & Sons. New York, NY.

Allen, E. and J. Iano. 2011. *The Architect's Studio Companion*, 5th ed. John Wiley & Sons. Hoboken, NJ.

ASHRAE. 2013. *ASHRAE Handbook—Fundamentals.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2013. ANSI/ASHRAE/IESNA Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2009. *Indoor Air Quality Guide: Best Practices for Design, Construction and Commissioning*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2007. ANSI/ASHRAE Standard 90.2-2007, *Energy-Efficient Design of Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2008. *ASHRAE Handbook—HVAC Systems and Equipment*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Ball State University. 2013. "Going Geothermal." http://cms.bsu.edu/about/geothermal

Barden, A. A. and H. Hyytiäinen. 1993. *Finnish Fireplaces: Heart of the Home*, 2nd ed. Finnish Building Centre, Ltd. Helsinki.

Bourne, R. and M. Hoeschele. 1998. "Performance Results for a Night Roof Spray Storage Cooling System," in *Proceedings of the 23rd National Passive Solar Conference*. American Solar Energy Society. Boulder, CO.

Calm, J. E. 1994. "Refrigerant Safety." *ASHRAE Journal*, July 1994.

Fitch, J. M. and W. Bobenhausen. 1999. *American Building: The Environmental Forces That Shape It*. Oxford University Press, New York, NY.

Grondzik, W. (ed.). 2007. *Air-Conditioning System Design Manual*, 2nd ed. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Haberl, J. S., J. Baltazar, and C. Mao. 2012. "Thermal Mass Modeling: How We Got To Where We Are Today." Energy Systems Laboratory, Texas A&M University. http://www-esl.tamu.edu/docs/terp/2012/ESL-TR-12-03-03.pdf.

Hydronics Institute Division of GAMA. 1996. *Installation Guide for Residential Hydronic Heating Systems*, No. 200. Berkeley Heights, NJ.

Mozer, M. 1998. "The Neural Network House: An Environment That Adapts to Its Inhabitants," in *Proceedings of the American Association for Artificial Intelligence, Spring Symposium on Intelligent Environments*. March 1998. Stanford University. Palo Alto, CA.

Natural Gas Cooling Equipment Guide, 4th ed. 1996. American Gas Cooling Center. Arlington, VA.

The New Buildings Institute. "Small Commercial HVAC System Design Guide." http://newbuildings.org/sites/default/files/A-12_Sm_HVAC_Guide_4.7.5.pdf

Ramsey, C. G. and H. R. Sleeper. 1994. *Architectural Graphic Standards*, 9th ed. American Institute of Architects/John Wiley & Sons. Hoboken, NJ.

Stein, J. and S. Taylor. 2013. "Reheat versus Active Chilled Beams & DOAS." *ASHRAE Journal* 55(5).

U.S. Environmental Protection Agency. "Energy Star-Labeled Heating and Cooling Equipment." http://www.energystar.gov/

C H A P T E R 13

Lighting Fundamentals

> Architecture is the masterly, correct and magnificent play of masses brought together in light. Our eyes are made to see forms in light; light and shade reveal these forms; cubes, cones, spheres, cylinders, or pyramids are the great primary forms which light reveals to advantage.
>
> — Le Corbusier

13.1 INTRODUCTORY REMARKS

FOR MANY YEARS, an unwarranted division existed in the field of lighting design, dividing it into two disciplines: architectural lighting and utilitarian design. The former found expression in design that took little cognizance of visual task needs and displayed an inordinate penchant for incandescent wallwashers, architectural lighting elements, and form-giving shadows. The latter saw all spaces in terms of illuminance levels and cavity ratios, and performed its design function with footcandles (lux) and dollars as the ruling considerations. That both of these trends have generally been eliminated is due largely to the efforts of thoughtful architects, engineers, and lighting designers, assisted in part by the energy consciousness that followed the 1973 oil embargo. The last event spurred research into satisfying vision needs within a framework of minimal energy use. That research, and its resulting energy codes and continuing development of higher-efficiency sources, are today motivated by environmental considerations.

Another positive factor in the rationalization of lighting design has been the work of the Illuminating Engineering Society of North America (IESNA). Its activities in research, standardization, and publication have done much to place lighting design on a stable scientific basis while taking full cognizance of its essential artistic aspects. It is precisely this combination of science and art that makes lighting design an architecture-type discipline. For each project, a responsible lighting designer will consider *quantitatively*:

1. Daylight—its introduction and integration with electric light
2. The interrelationship between the energy aspects of electric lighting and daylighting, heating, and cooling
3. The effect of lighting on interior space arrangements, and vice versa
4. The characteristics, means of generation, and utilization techniques of electric lighting
5. The visual needs of specific occupants and of specific tasks
6. The effects of brightness patterns on visual acuity

And *qualitatively*:

7. The location, interrelationship, and psychological effects of light and shadow—that is, brightness patterns

8. The use of color, both of light and of surfaces, and the effect of the illuminant source on object color—and sometimes the reverse
9. The artistic effects possible with patterns of light and shadow, including the changes inherent in daylighting, and so on
10. Physiological and psychological effects of the lighting design, particularly in spaces occupied for extended periods

The list is almost endless, because so much of the information we receive from our senses comes via our eyes, and what we see is a direct consequence of scene lighting.

PHYSICS OF LIGHT

13.2 LIGHT AS RADIANT ENERGY

The IESNA defines light as visually evaluated radiant energy or, more simply, as a form of energy that permits us to see. If light is considered as a wave, similar to a radio wave or an alternating-current wave, it has a frequency and a wavelength. Figure 13.1 shows the position of light in the wave spectrum and its relation to other wave phenomena of various frequencies.

From Fig. 13.1 we see that even the longest-wavelength light (red) has a much higher frequency than radio waves and radar, and that light constitutes only a very small part of the wave energy spectrum. Color is determined by wavelength—starting with the longest wavelengths (lowest frequency), which are perceived as red, on through the shortest visible wavelengths (highest frequency), which encompass the spectrum of what we recognize as orange, yellow, green, blue, indigo, and violet. Bordering the visible spectrum, on the low-frequency end, is the infrared; at the high-frequency end lies the ultraviolet. Both are invisible to human beings but not to some animals.

When a light source produces energy over the entire visible spectrum in *approximately* equal quantities, the combination appears white, whereas a source producing energy over only a small section of the spectrum produces its characteristic colored light. Examples are the blue–green clear mercury lamp and the yellow sodium lamp.

For our purposes, all light will be considered white unless specifically noted otherwise. This position is scientifically tenable because light sources with large differences in chromatic content all appear white after a short accommodation period, and all standard commercial sources permit colors

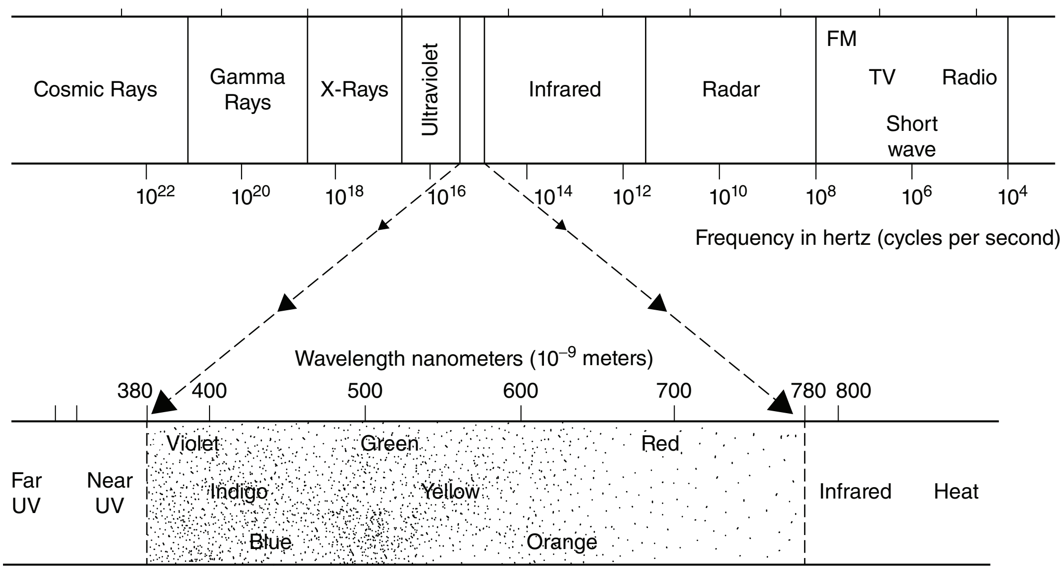


Fig. 13.1 *Electromagnetic spectrum.*

to be easily and correctly identified. It is only when sources differing widely in chromaticity are viewed side by side, that the variation in whiteness can be noticed by the effect on colored objects and on neutral surfaces.

13.3 TRANSMITTANCE AND REFLECTANCE

Lighting design is possible because light is predictable; that is, it obeys certain laws and exhibits certain fixed characteristics. Although some of these are so well known as to appear self-evident, a review is in order.

The *luminous transmittance* of a material such as a luminaire lens or diffuser is a measure of its capability to transmit incident light. By definition, this quantity, known variously as *transmittance*, *transmission factor*, and *coefficient of transmission*, is the ratio of the total transmitted light to the total incident light. In the case of incident light containing several spectral components passing through a material that displays *selective* absorption, this factor becomes an average of the individual transmittances for the various components and must be used cautiously. A piece of frosted glass and a piece of red glass may both have a 70% transmission factor, but they affect the incident light differently. In general, then, transmission factors should be used only when referring to materials displaying nonselective absorption—that is, those that transmit the various component colors equally. Clear glass, for instance, displays a transmittance between 80% and 90%, frosted glass between 70% and 85%, and solid opal glass between 15% and 40%. The remainder is absorbed and reflected. See Table 8.8 for typical transmission factors.

Similarly, the ratio of reflected light to incident light is variously called *reflectance*, *reflectance factor*, and *reflectance coefficient*. Thus, if half the amount of light incident on a surface is bounced back, the reflectance is 50% (or 0.50). The remainder is absorbed, transmitted, or both. The amount of absorption and reflection depends on the type of material and the angle of light incidence, because light impinging on a surface at grazing angles tends to be reflected rather than absorbed or transmitted (Fig. 13.2).

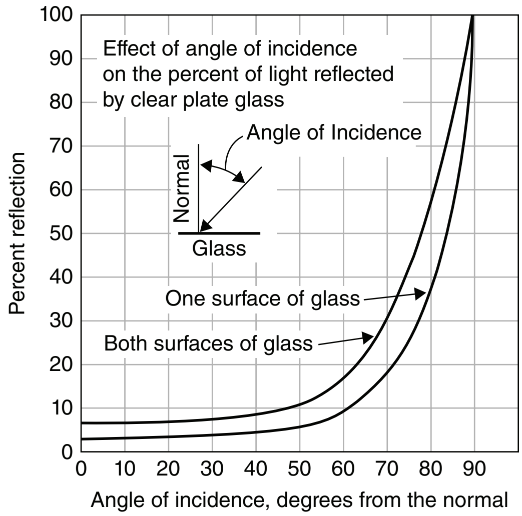
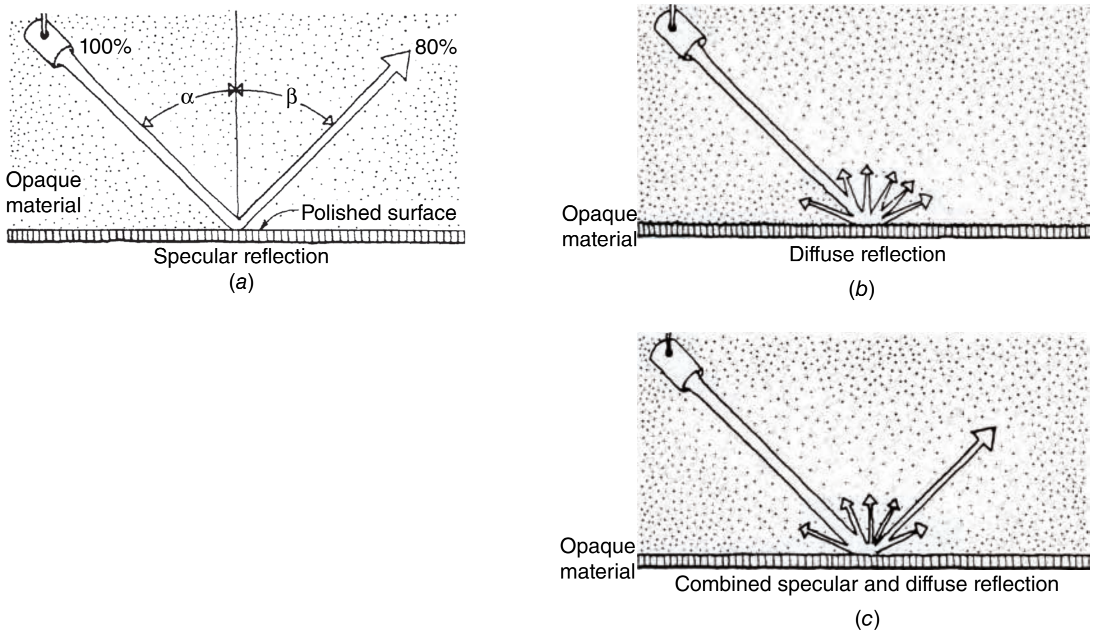


Fig. 13.2 *Relation between angle of incidence and percentage of reflectance. This effect is important when considering the penetration of sunlight into interior spaces and, conversely, the exterior glare produced by reflection of the sun from building windows.*

An example of almost perfect reflection from an opaque surface would be that from a well-silvered mirror, whereas almost complete absorption takes place on an object covered with lamp black or matte-finish black paint. The effect of the material's surface finish on reflection is shown in Fig. 13.3. See Table 8.10 for typical reflectance values. Reflectance measurement is discussed in Section 13.7.

The reflection that occurs on a smooth surface such as polished glass or stone is called *specular reflection*, as in Fig. 13.3*a*. If the surface is rough, multiple reflections take place on the many small surface projections, and the light is diffused, as in Fig. 13.3*b*. Reflectance is a measure of total light reflected; it may be specular or diffuse, or a combination of both, as shown in Fig. 13.3*c*.

Diffuse transmission takes place through any translucent material such as frosted glass, white glass, milky Plexiglas, tissue paper, and so on. This diffusing principle is widely employed in lighting fixtures (luminaires) to spread the light generated by the source located within the fixture. Diffuse and nondiffuse transmissions are illustrated in Fig. 13.4*a* and Fig. 13.4*b*.



Interactive Animation

Fig. 13.3 *Reflection characteristics. (a) In specular reflection, angle of incidence equals angle of reflection ($\alpha = \beta$). Because 80% of light is reflected, reflectance is 80%; 20% of light is absorbed. (b) In diffuse reflection, incident light is spread in all directions by multiple reflections on the unpolished surface. Such surfaces appear equally bright from all viewing angles. (c) Most materials exhibit a combination of specular and diffuse reflection. Such a surface mirrors the source while producing a bright background.*

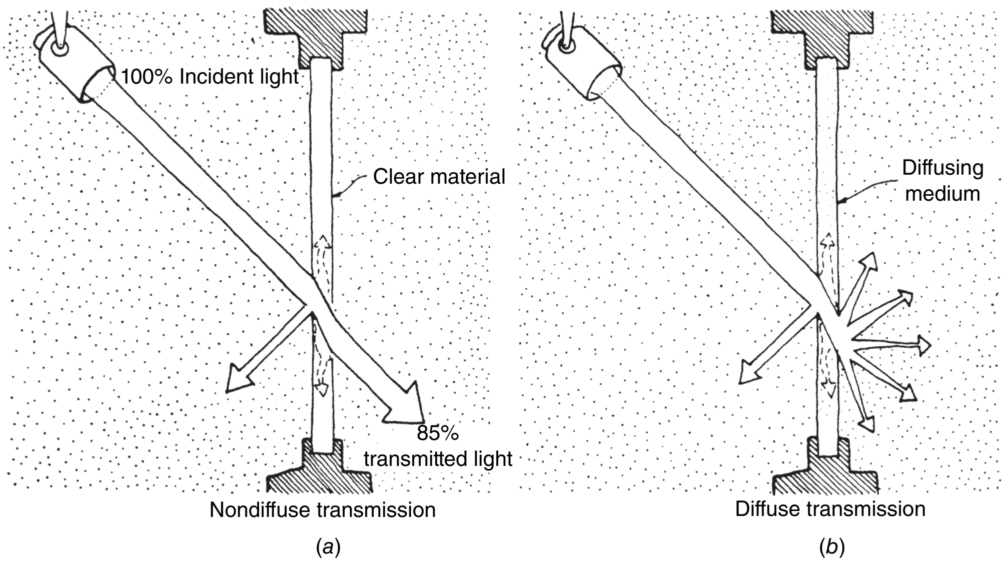


Fig. 13.4 *Transmission characteristics. (a) In nondiffuse transmission, the light is refracted (bent) but emerges in the same beam as it enters. Clear materials such as glass, water, and certain plastics exhibit this type of transmission. In the instance illustrated, the transmittance is 85% (the remaining 15% is reflected and absorbed). The source of light is clearly visible through the transmitting medium. (b) With diffuse transmission, the source of light is not visible and, in the case of multiple sources, the diffusing surface exhibits generally uniform brightness if the spacing between the light sources does not exceed approximately 1½ times their distance from the material.*

13.4 TERMINOLOGY AND DEFINITIONS

Before beginning any discussion of lighting studies, techniques, and effects, it is important to have a basic understanding of the physical concepts and terminology involved, as well as their interrelations. The Système International (SI) system of units is used as the basic system by the IESNA and in this book, whereas the lighting industry uses both the SI and inch-pound (I-P) systems. As in other chapters, we frequently use dual units, with the second unit enclosed in parentheses.

(a) Luminous Intensity

The SI unit of *luminous intensity* is the candela (candlepower), abbreviated cd (cp), and normally represented by the letter *I*. It is analogous to pressure in a hydraulic system and voltage in an electric system, and represents the force that generates the light that we see. An ordinary wax candle has a horizontal luminous intensity of approximately 1 candela, hence the name. The candela and candlepower have the same magnitude. Luminous intensity is a characteristic of the source only; it is independent of the visual sense.

(b) Luminous Flux

The unit of luminous flux, in both SI and I-P units, is the lumen (lm). If we take a 1-cd (candlepower) source that radiates light equally in all directions and surround it with a transparent sphere of 1 m (ft) radius (Fig. 13.5), then *by definition* the amount of luminous energy (flux) emanating from 1 m^2 (ft^2) of surface on the sphere is 1 lm. Because there is 4π m^2 (ft^2) surface area in such a sphere, it follows that a source of 1 candela (candlepower) intensity produces 4π, or 12.57, lm. The lumen, as luminous flux, or quantity of light, is analogous to flow in hydraulic systems and current in electric systems and is normally represented by the Greek letter ϕ.

In physical terms, the lumen is a unit of power, like the watt. However, unlike the watt, which is a radiometric unit directly convertible to other power units such as Btu/h, the lumen is a measure of *photometric* power. This means light power as perceived by the human eye and therefore as a function of human physiology. Put another way, a lumen, or luminous flux, is the time rate of flow of *perceived* luminous energy. Because the visual response of the eye is frequency dependent, the apprehended light power is therefore also frequency dependent, varying with the spectral content of the impinging

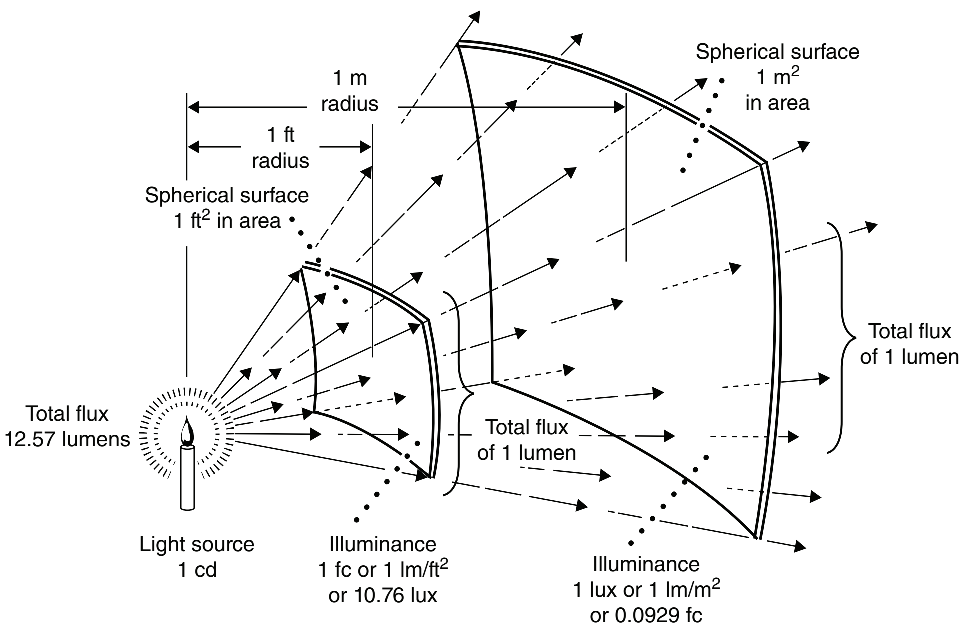


Fig. 13.5 *A source of 1-cd intensity produces 4π (12.57) lumens of light flux. Thus, each square foot (square meter) of spherical surface surrounding such a source receives 1 lumen of light flux. This quantity of light flux produces an illuminance of 1 fc (lux) on the spherical surface.*

light and the spectral sensitivity of the eye. Figure 13.6*a* shows the spectral content of the visible energy produced by a 500-W incandescent lamp. Measured radiometrically, it amounts to 45 W. However, when passed through a selective filter (Fig. 13.6*b*), which is effectively what happens when the light enters the eye, the resultant "understood" light power appears as in Fig. 13.6*c*, and therefore can no longer be measured in watts. Instead, we use a unit of eye-perceived, or photometric, power called the *lumen*. If the spectral content curve in Fig. 13.6*a* were differently shaped, *even if the total radiometrically measured power were the same*, the resultant perceived power in Fig. 13.6*c* would be different.

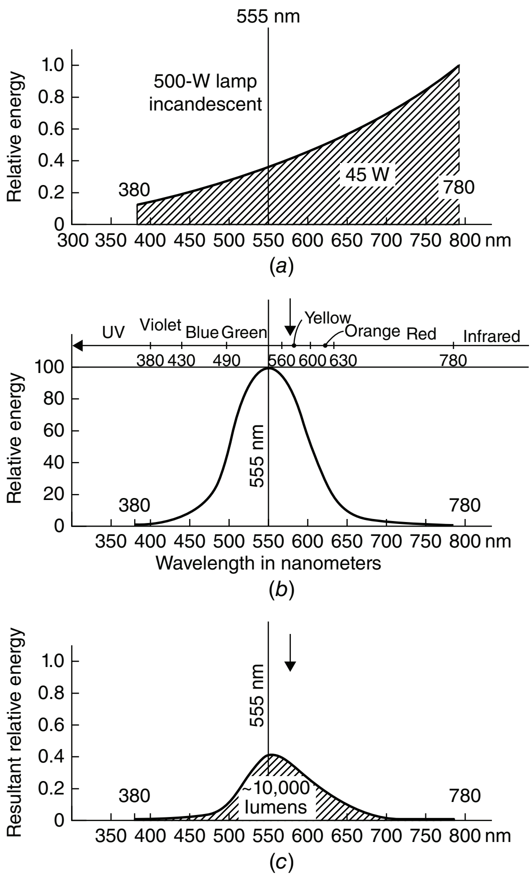


Fig. 13.6 Graphical demonstration of the method by which the unit of light flux is defined. (a) The spectrum of the light produced by a 500-W incandescent lamp. It amounts to approximately 45 W measured radiometrically. When filtered by the human eye, whose spectral sensitivity curve is given in (b), this light power is perceived as shown in (c). The new light power curve is expressed in lumens and indicates the quantity of light as perceived by the eye.

Refer to Fig. 13.6*b*. A correlation can be made between photometric and radiometric power at the point of maximum response of the eye, which occurs at 555 nanometers (nm) wavelength—1 nm is 10^{-9} m. One watt of monochromatic light at that wavelength produces 683 lm. However, because common light sources such as incandescent, fluorescent, mercury, and so on, are not monochromatic, but produce light in many parts of the spectrum (see Figs. 13.47 and 13.48 and Table 13.8), no single conversion factor between watts and lumens exists. Each source has its own luminous efficiency (lumens/watt), determined by its spectrum. For the 500-W lamp used as an illustration in Fig. 13.6, its luminous efficiency (efficacy) is 10,000 lm/500 W, or 20 lumens per watt (lm/W or lpw).

(c) Illuminance

One lumen of luminous flux, uniformly incident on 1 m^2 (ft^2) of area, produces an *illuminance* of 1 lux (lx) (*footcandle* [fc]). Illuminance is normally represented by the letter *E*. Restated, illuminance is the density of luminous power, expressed in terms of lumens per unit area. If we consider a light bulb as analogous to a sprinkler head, then the rate of water flow would be the lumens, and the amount of water per unit of time, per m^2 (ft^2) of floor area, would be the lux (footcandles). Thus, the SI unit, lux, is smaller than the corresponding I-P unit, footcandles, by the ratio of square meters to square feet. That is,

$$10.764 \text{ lux} = 1 \text{ fc}$$

or multiply footcandles by 10.764 to obtain lux. These relationships are shown in Fig. 13.5. Restating mathematically yields

$$\text{lux} = \frac{\text{lumens}}{\text{square meter area}} \tag{13.1}$$

$$\text{lx} = \frac{\text{lm}}{\text{m}^2}$$

and

$$\text{footcandles} = \frac{\text{lumens}}{\text{square foot area}} \tag{13.2}$$

$$\text{fc} = \frac{\text{lm}}{\text{ft}^2}$$

As an *approximation* (with 8% error)

$$10 \text{ lx} \approx 1 \text{ fc} \tag{13.3}$$

EXAMPLE 13.1 A 34-W, 425-mA (milliampere), 48-in. (122-cm) fluorescent tube produces 3200 lm. What is the illuminance on the floor of a 3-m^2 room, assuming 60% overall efficiency and uniform illumination?

SOLUTION

Useful lumens = 0.6 × 3200 = 1920

$$\text{lx} = \frac{1920}{3 \times 3} = 213.3 \text{ lx}$$

$$\text{fc} = 213.3 / 10.76 = 19.8 \text{ fc}$$

Calculating footcandles directly, we obtain (with 3 m = 9.84 ft)

$$\text{fc} = \frac{1920}{9.84 \times 9.84} = 19.8 \text{ fc}$$

By approximation:

$$\text{fc} \cong \text{lx}/10 = 21.3$$

Note that this calculation gives *average* illuminance in the space. Illuminance at a *point* can be computed from intensity, as explained in Section 13.8. ■

TABLE 13.1 Lighting Units—Conversion Factors

Unit	Multiply	By	To Obtain
Illuminance (*E*)	Lux	0.0929	Footcandle
	Footcandle	10.764	Lux
Luminance (*L*)	cd/m^2	0.2919	Footlambert
	cd/cm^2	10,000	cd/m^2
	cd/in.^{2}	1,550	cd/m^2
	cd/ft^2	10.76	cd/m^2
	millilambert	3.183	cd/m^2
	Footlambert	3.4263	cd/m^2
Intensity (*I*)	Candela	1.0	Candlepower

(d) Luminance, Exitance, and Brightness

An object is perceived because light coming from it enters the eye. The impression received is one of object *brightness*. This brightness sensation, however, is subjective and depends not only upon the object *luminance* (*L*), but also upon the state of adaptation of the eye (see Section 13.12). For this reason, the physiological sensation is generally referred to in the literature as *subjective* or *apparent brightness*, or simply *brightness*, whereas the measurable, reproducible state of object luminosity is its *luminance* (formerly *photometric brightness*). Luminance is normally defined in terms of intensity; it is the luminous intensity per unit of *apparent* (projected) area of a primary (emitting) or secondary (reflecting) light source. Thus, its units are candela per area. Specifically, the SI unit of luminance is candela per square meter (cd/m^2), sometimes referred to as the *nit*. Another unit, formerly in common use in the I-P system, is the footlambert. Conversion factors for SI and I-P units (plus other, obsolete units for the convenience of readers using older sources) are given in Table 13.1. Other luminance terms such as *stilb*, *apostilb*, *blondel*, *millilambert*, and *candela per square in.* are best avoided. In this book, the term *luminance* is used except where it is specifically intended to refer to the physiological sensation involved, in which case the terms *brightness*, *subjective brightness*, or *apparent brightness* will be used. Luminance has no readily conceivable mechanical or electrical analogy.

A word of caution is appropriate at this point. Although definitions and terminology are established for the specific purpose of accurate information exchange, the lighting literature is replete with articles, comments, and rebuttals that exist only because of the looseness of definitions and terminology. Some authors insist on applying *brightness* only to self-luminous surfaces, using *lightness* as the equivalent term for objects deriving their luminance from reflection. Thus, the sun has brightness, the moon—lightness. In this book, we use the term *brightness* for the subjective reaction to either source type. Other sources point out that the luminance–brightness relation breaks down when non-white light is used. Although this is demonstrable, it is of real interest only in theatrical lighting, where colored light is frequently used. For our purposes we assume white light, and, as pointed out previously, the color accommodation characteristic of our eyes recognizes a large chromatic range as white (colorless) light. Within that range, and for a very large range of intensities, object color is readily recognizable, and the fixed luminance–brightness ratio is maintained. Contrasting word usages such as *dim* and *dark*, *light* and *bright*, *clear* and *muddy*, *shallow* and *deep*, and so on, as applied to lighting, are best left to experienced lighting designers because the terms are almost entirely subjective and therefore unhelpful to novice designers.

Another concept that the lighting designer will encounter is known as *luminous exitance*, or simply as *exitance*, which, as the name implies, describes the total luminous flux density leaving (exiting) a surface, irrespective of directivity or viewer position. For instance, if a 1 m^2 surface emits 1 lumen, its luminous exitance is 1 lumen per square meter (1 lm/m^2) or 0.093 lm/ft^2. A surface that is a perfect diffuser, whether by emitting light diffusely or reflecting light diffusely, is known as a *lambertian surface*. It is fairly simple to demonstrate mathematically that the luminance of such a surface equals $1/\pi$ times its exitance. The importance of this relationship is its usefulness as an approximation. Although very few surfaces are truly lambertian, many are approximately so, and this relationship can be used as an engineering-accuracy approximation in many such cases.

The concept of exitance is important in detailed photometric calculations—such as those involved in determining coefficients of utilization and surface luminance coefficients—and in detailed point illuminance calculations. All of these are beyond the scope of this book because they are not usually performed by the lighting designer. Use of the derived coefficients is demonstrated in the applicable sections.

Detailed point calculations are today almost universally performed by computer, and the necessary mathematics is built into the computer program. Readers interested in further background on luminous exitance are referred to Murdoch (1985).

Because object luminance is that which is visually perceived and is a prime factor in visibility (and glare), it is important that the reader be able to perform basic luminance calculations. Although the eye does not differentiate between primary sources that generate and emit light and secondary sources that derive their luminance from reflection or transmission, the differentiation is important in calculation procedures. See Fig. 13.7 for a graphic representation of the basic relationships.

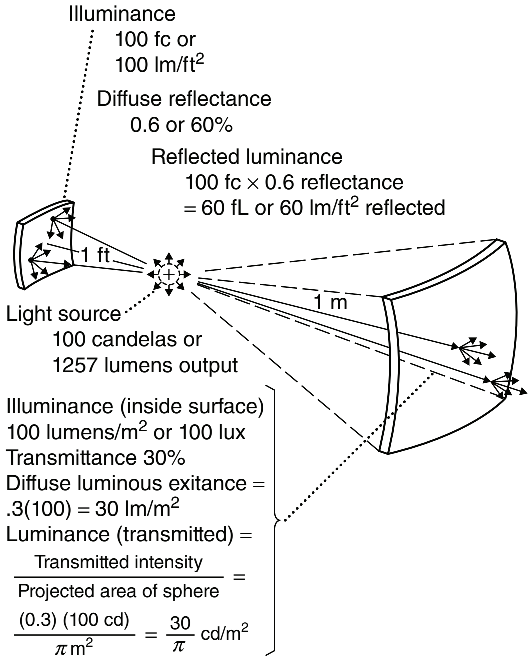


Fig. 13.7 *Luminance may be the result of either reflection or transmission. In the former case, it is calculated as the product of the incident lumens and the reflectance; in the latter case, it is calculated as the transmitted intensity divided by the projected area.*

EXAMPLE 13.2 Luminance of a light-emitting surface.

1. Calculate the luminance of an historic A-19 standard inside-frosted, 100-W incandescent light bulb with a maintained output of 1700 lm. Assume (for simplicity's sake) that the bulb is spherical.
2. Assume that an opal glass globe of 8-in. (200-mm) diameter and a transmittance of 35% surrounds the bulb described in step 1. Calculate the luminance of the globe. Use SI units throughout.

SOLUTION

1. Assume that the filament is a point source (an essentially valid assumption) and that the inside frosting of the glass does not reduce the output (it actually does so by about 1%). The inside frosting acts to convert the point source filament to a uniformly emitting globe. The definition of a point source tells us that 1 candela produces 4π lumens distributed spherically.

Therefore:

$$\frac{1\text{cd}}{4\pi\,\text{lm}} = \frac{I\text{ cd}}{1700\,\text{lm}}$$

The intensity, I, of the filament, and therefore also of the bulb (because the frosting is assumed not to reduce output), is

$$I = 1700\text{ lumens} \times \frac{1\text{cd}}{4\pi\text{ lm}} = 135\text{ cd}$$

An A-19 bulb has a diameter of 19/8 in. (60 mm). The definition of luminance is

$$L = \frac{I}{A} \frac{\text{(intensity)}}{\text{(projected area)}}$$

The projected area becomes approximately a circle with a diameter of 60 mm (assuming a spherical bulb), whose area equals πr^2 or $\pi\,(0.03\text{ m})^2$. So

$$L = \frac{135\text{ cd}}{\pi(0.03\text{ m})^2} = 47{,}750\,\frac{\text{cd}}{\text{m}^2}$$

This luminance is a potentially severe glare source if it is in the field of vision (depending on its distance from the eye; see Section 13.17).

2. We have already calculated the intensity of the source, but it is reduced to 35% by the globe. The projected area of the globe is larger than that of the bulb; that is,

$$\text{A proj.} = \pi r^2 = \pi \frac{(0.2\text{ m})^2}{(2)}$$

So the expression for luminance becomes

$$L = \frac{135\text{ cd }(0.35)}{\pi\ (0.10\text{ m})^2} = 1500\,\frac{\text{cd}}{\text{m}^2}$$

This is no longer a potential source of direct glare. ■

Note two important principles demonstrated by this example:

1. Intensity is neither area- nor distance-dependent; it varies only with transmission factors.
2. Luminance varies with both intensity and area.

For example, if a white lamp whose inside coating reduces lamp output by about 10% is used in lieu of an inside frost, both intensity and luminance would be reduced by 10%. However, if a clear glass lamp is used, intensity would remain the same, while luminance would increase inversely with the ratio of filament area to bulb area. Therefore, a clear 100-W lamp, whose filament has an area of perhaps of 0.3 cm^2, would have a luminance of

$$\frac{135\text{ cd}}{0.3\ (0.0001)\text{ cm}^2} = 4{,}500{,}000\text{ cd/m}^2$$

which is so severe a glare source as to be disabling when in the near field of vision.

EXAMPLE 13.3 Calculate the luminance of a 34-W, T12, 4-ft white fluorescent lamp. Assume a viewing angle normal to the long axis of the lamp and that the lamp is a diffuse (lambertian) emitter. Use SI units.

SOLUTION

This problem can be solved in two ways: by using the relationship between exitance and luminance or by calculating intensity.

By exitance/luminance: Use 2770 lm at 40% life as an average condition of lamp output. The luminous length is 4 ft (1200 mm), and the diameter is 12/8 in. (38 mm). The luminous surface area of the tube is then

$$\begin{aligned} A &= L \times d \times \pi = (1200\text{ mm}) \times (38\text{ mm}) \times \pi \\ &= (1.2\text{ m})\ (0.038\text{ m}) \\ &= 0.0456\ \pi\text{ m}^2 \end{aligned}$$

$$\text{exitance} = \frac{\text{luminous flux}}{\text{area}} = \frac{2770\text{ lm}}{0.0456\ \pi\text{ m}^2}$$

$$\begin{aligned} \text{luminance} &= \frac{I}{\pi}\ \text{(exitance)} \\ &= \frac{2770}{0.0456\,\pi^2}\ \text{cd/m}^2 = 6155\text{ cd/m}^2 \end{aligned}$$

By intensity: The equivalent spherical intensity of the lamp can be calculated by using the relationship that 1 cd produces 4π lumens. Therefore,

$$\text{equivalent intensity } I = \frac{2770\text{ lm}}{4\pi}\ \text{cd}$$

The radius of a sphere of equivalent surface area to the fluorescent tube would be

$$4\,\pi\,r^2 = 0.0456\ \pi\text{ m}^2$$

$$r^2 = \frac{0.0456}{4}\ \text{m}^2 = 0.0114\text{ m}^2$$

$$r = 0.1067\text{ m}$$

The equivalent projected area of such a sphere is $\pi\,r^2$, or

$$A = 0.0114\ \pi$$

and its luminance is

$$\begin{aligned} L &= \frac{\text{intensity}}{\text{area}}\frac{\text{cd}}{\text{m}^2} = \frac{2770/4\,\pi}{0.0114\pi}\frac{\text{cd}}{\text{m}^2} \\ &= \frac{2770}{0.0456\,\pi^2}\frac{\text{cd}}{\text{m}^2} \\ &= 6155\text{ cd/m}^2 \end{aligned}$$

This luminance can constitute a glare problem, depending on its position in the field of view. If we had used a 40-W lamp with 3200 lm output, its luminance would be higher in direct proportion to the ratio of output; that is,

$$L_{3200} = L_{2770} \times \frac{3200}{2770} = 6155\ \frac{\text{cd}}{\text{m}^2}\ \frac{(3200)}{(2770)}$$

$$= 7110\ \text{cd/m}^2$$

This is the origin of the frequently used average figure of 7000 cd/m^2 as the luminance of a standard 48-in. (1200 mm) fluorescent tube. It is a borderline glare source.

Because of its energy-saving characteristic, the 32-W, 48-in. T8 lamp with 3000 lm output has come into wide use. That it should not be used unshielded can be readily demonstrated by a similar luminance calculation:

Tube area = $L \times \pi\, d$

$$= (120\ \text{cm})(\pi)8/8\ \text{in.}\left(2.54\frac{\text{cm}}{\text{in.}}\right)$$

$$= 958\ \text{cm}^2 = 0.0958\ \text{m}^2$$

$$\text{exitance} = \frac{\text{lumens}}{\text{area}} = \frac{3000\ \text{lm}}{0.0958\ \text{m}^2} = 31{,}330\ \text{lm/m}^2$$

$$\text{luminance} = \frac{1}{\pi}\ (\text{exitance}) = \frac{31{,}300}{\pi} = 9972$$

or approximately 10,000 cd/m^2. Because this level of luminance is potentially a mild glare problem, these lamps should not be used in bare-bulb fixtures. ■

EXAMPLE 13.4 To demonstrate the usefulness of the luminance/exitance approximation, calculate the luminance, in SI units, of the page that you are now reading. Assume a uniform illuminance of 500 lx, a diffuse reflectance of 0.77, and a viewing angle normal to the page.

SOLUTION

From the definition of illuminance, 1 lx is produced by 1 lm falling on 1 square meter. Therefore, the exitance, or density of reflected lumens from the page, is

$$\text{exitance} = \frac{500\ \text{lm}}{\text{m}^2} \times 0.77 = 385\ \frac{\text{lm}}{\text{m}^2}$$

and

$$L = \frac{1}{\pi} \times 385\ \frac{\text{lm}}{\text{m}^2} = 122.5\ \text{cd/m}^2$$

(Typical luminances are given in Table 13.2; see Section 13.12.) ■

13.5 ILLUMINANCE MEASUREMENT

Field measurements of illuminance levels are most commonly made with a portable illuminance meter, two examples of which are illustrated in Figs. 13.8 and 13.9. These devices contain a photoelectric material connected to a microammeter via electronic control circuitry and are calibrated in lux, footcandles, or both.

As explained in Section 13.6 and as shown in Fig. 13.6, the human eye is not equally sensitive to the various wavelengths encompassed by the visible spectrum. Maximum sensitivity at high illuminance levels is in the yellow–green area (wavelength of 555 nm), whereas sensitivity at the red and blue ends of the spectrum is quite low. This effect is so pronounced that 10 units of blue energy are required to produce the same visual

Fig. 13.8 *Electronic, digital, color-corrected and cosine-corrected light (illuminance) meter from Konica-Minolta.*

Fig. 13.9 *Digital meter (from Li-Cor) has a variety of sensors that measure illuminance, solar irradiance, or photosynthetic radiation. Due to its small size, the illuminance sensor can be easily used for architectural model measurements.*

effect as 1 unit of yellow–green. Therefore, if a meter is to be useful, its inherent response, which is quite different from that of the human eye, must be corrected to correspond to the eye. For this reason, meters are "color corrected."

The cells (meters) must also be corrected for light incident at oblique angles that does not reach the cell due to reflection from the surface glass and shielding of the light-sensitive cell by the meter housing. This correction is known as *cosine correction*. A good meter must therefore be color and cosine corrected (and will plainly so indicate).

Modern photometers may have considerable electronic circuitry, which provides such functions as automatic ranging, integration for flickering or time-varying sources, and connection facilities for data storage and transmission. For determining average room illuminance when using a conventional non-integrating meter, a number of readings should be taken and an average computed. Where no definite height is specified, readings are taken at 30 in. (750 mm) above the floor, a level known as the *working plane* because it is approximately normal desk height. The meter must always be held with the cell parallel to the plane of the test. Thus, to measure wall illuminance, the meter must be held with the cell parallel to the wall. If electric lighting readings are desired and the test is being conducted during daylight hours, readings should be taken with and without the electrical illumination, and the results subtracted. Detailed instructions for conducting field surveys are contained in the IESNA publication *How to Make a Lighting Survey*. Briefly, a survey of an existing indoor lighting installation should establish:

1. Type, rating, and age of sources
2. Type, design, and model of luminaires
3. Maintenance schedule

It should also measure:

1. Mounting height of luminaires
2. Spacing and pattern of luminaires
3. Reflectances of walls, floor, ceiling, and major items of furniture and equipment
4. Illuminance levels throughout the area, plus levels at all working plane elevations.
5. Vertical surface illuminance at walls and other major vertical planes (the significance of vertical surface luminance is discussed in detail in subsequent chapters)

13.6 LUMINANCE MEASUREMENT

In terms of appreciation of the visual scene, including particular considerations of glare, the measurement of luminance is more important and meaningful than that of illuminance (lux [fc]). This is so because it is luminance—or, more accurately, subjective brightness and brightness contrasts caused by photometric luminance—that we see, not illuminance. Light, as such, is invisible. That illuminance measurements are still more widely taken than luminance measurements and utilized as a gauge of the adequacy of a lighting installation is due to two factors:

1. Lux meters are cheaper and simpler to use than luminance meters.
2. Design recommendations for lighting levels are given in terms of illuminance. Lux measurements can therefore be used as a rapid, simple method of determining whether a particular lighting installation meets these

Fig. 13.10 *Direct-reading, narrow-angle, spot-type luminance meter has an acceptance angle of 1°, a range of 0.001 to 299,000 cd/m² (0.001 to 87,000 fL), a variable response speed to permit measurement of flickering sources, and a comparison mode that permits direct luminance comparison of two situations. Results are displayed digitally.*

Fig. 13.11 *When the cell of a direct-reading illuminance meter is held in contact with a luminous source, the surface luminance can be read directly or calculated.*

design requirements (assuming that material reflectances and reflectance ratios are correctly chosen).

Luminance meters are available in a number of configurations, one of which is shown in Fig. 13.10. An approximation of the luminance of a reflecting or luminous source can be obtained using an illuminance (footcandle) meter of the type shown in Fig. 13.8. For diffuse *reflecting* surfaces, the cell of the meter is placed against the surface and then slowly retracted 2 to 4 in. (50 to 100 mm) until a constant reading is obtained. The luminance, in footlamberts, is then approximately 1.25 times the reading in footcandles, the 1.25 factor compensating for wide-angle losses.

For a diffuse luminous source, the cell of an illuminance meter is placed directly against the surface (Fig. 13.11); the source luminance in footlamberts is equal to the reading on the meter in footcandles because footlamberts = lumens per area = footcandles. When using a meter calibrated in lux, the readings must be divided by π to obtain the diffuse source luminance in cd/m^2.

13.7 REFLECTANCE MEASUREMENTS

It is often desirable to know the reflectance of a given surface because luminance can then be readily computed (see Fig. 13.7). Two methods of measuring diffuse (non-specular) reflectance are shown in Fig. 13.12: the known-sample method and the light-ratio method. If a sample of known reflectance is available, this method should be used because it yields more accurate results than the ratio method. The sample should be no smaller than 8 in. × 8 in. (200 mm × 200 mm).

It is a good idea for an inexperienced lighting designer to determine the reflectances, illuminance, and luminance levels of spaces and surfaces familiar to him or her, such as an office desk, adjoining wall, and the like—even to the extent of marking these figures on the respective surfaces in order to develop an appreciation of, and a memory for, these parameters. This enables the designer to visualize the result of a lighting design and should be of considerable assistance. See Table 8.10 for typical reflectance values.

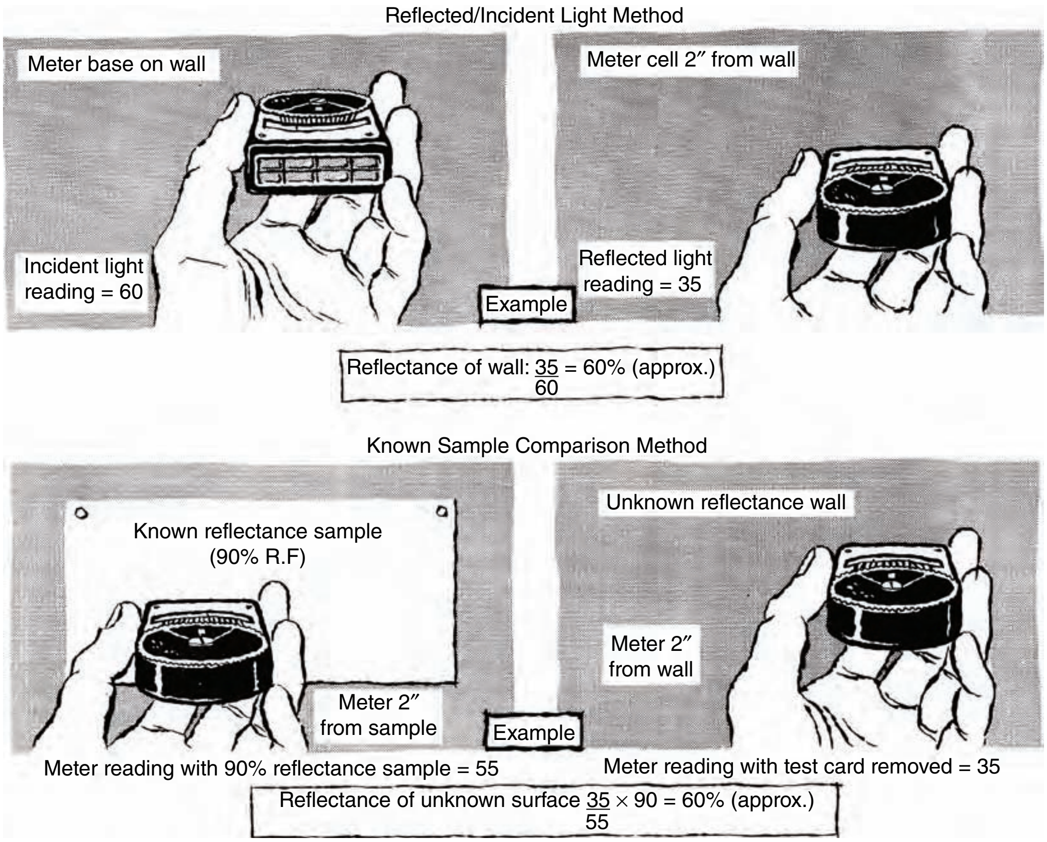


Fig. 13.12 *Two simple methods of measuring the diffuse reflectance of a surface.*

13.8 INVERSE SQUARE LAW

We have already seen that, by definition, a point source of 1-cd intensity produces an illumination of 1 lux on the inside surface of a surrounding sphere of 1-m radius (r). Because the surface area of this sphere is 4π m^2, a 1-cd source produces 4π lm of luminous flux. Now, assume a sphere of 2-m radius surrounding this same source (Fig. 13.13). Because the same amount of flux is spread over a larger area, the illumination on the larger sphere is inversely proportional to the ratio of the sphere areas; that is,

$$\frac{\text{lux}_2}{\text{lux}_1} = \frac{\text{area}_1}{\text{area}_2} \tag{13.4}$$

or

$$\text{lux}_2 = \text{lux}_1 \times \frac{\text{area}_1}{\text{area}_2}$$

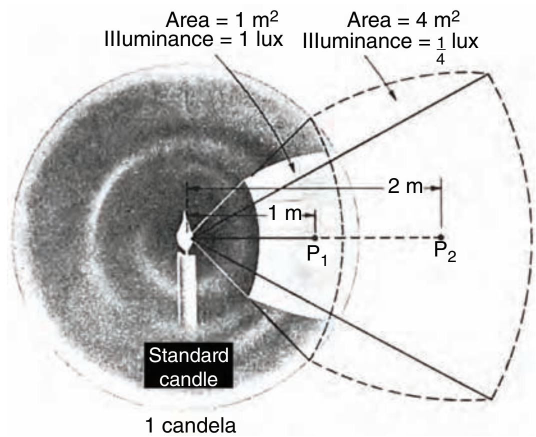


Fig. 13.13 *Relationship among candelas, lumens, and lux defined with reference to a standard light source of 1 mean spherical cp (1 cd) located at the center of a sphere with a 1-m radius.*

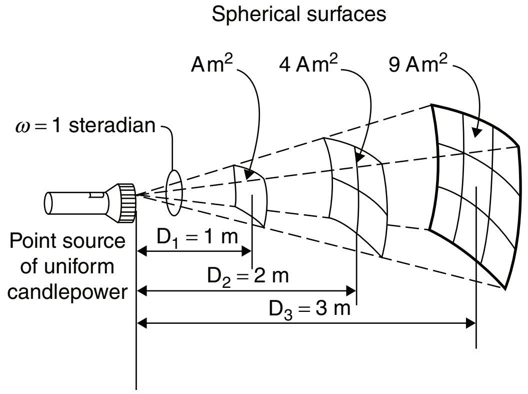


Fig. 13.14 *Demonstration of inverse square law properties using a solid angle of unit size. Note that the surfaces are necessarily spherical because points on a planar surface are not equidistant from the source.*

therefore,

$$\mathrm{lux}_2 = \mathrm{lux}_1 \times \frac{4\pi r_1^2}{4\pi r_2^2} \tag{13.5}$$

$$= \mathrm{lux}_1 \times \frac{r_1^2}{r_2^2}$$

In other words, the illuminance is inversely proportional to the square of the distance from the source. In general terms,

$$\mathrm{lux} = \frac{\text{cd intensity}}{\text{distance}^2} \tag{13.6}$$

where distance is expressed in m (ft). (This holds true for surfaces normal to a source.)

This relationship can also readily be derived by using any solid angle and the area it intercepts, as in Fig. 13.14. A glance at this figure shows clearly that the area intercepted is proportional to the square of the distance from the source; therefore, the illuminance is inversely proportional, as stated previously.

13.9 LUMINOUS INTENSITY: CANDELA MEASUREMENTS

Luminous intensity (candela [candlepower]) cannot be measured directly but must be computed from its illumination effects. The simplest way of doing this is to use the inverse square relationship developed in the preceding section: Measure the illuminance produced on a plane at right angles to the source at a known distance and apply Equation 13.6. For accurate measurement, the distance should be at least 5 and preferably 10 times the maximum dimension of the source because, for anything other than a point source, the equation is an approximation. The candela (candlepower) thus calculated is the luminous intensity in the direction being viewed. Because luminous intensity is not uniform in all directions for anything except an ideal point source, and because a single intensity figure for a source is desirable for calculation purposes, the average of a number of intensity figures taken from several directions is used. This average figure is called the *mean spherical candlepower* (mscp) and represents an equivalent point source that produces 4π lm for every candela. Thus, a 10-cd lamp exhibits an average intensity of 610 cd in all directions and produces 40π lm.

13.10 INTENSITY DISTRIBUTION CURVES

If the luminous intensity figures calculated in the preceding section are plotted on polar coordinate axes, the resultant figure is called a *candlepower distribution curve* (CDC) for the particular source involved. The procedure for making this curve is straightforward. A photo cell is rotated around the source in a single plane, illuminance is measured, and intensity (cd) is calculated. Alternatively, the photo cell can be fixed and the source rotated. If the source's distribution is symmetrical, as shown in Fig. 13.15,

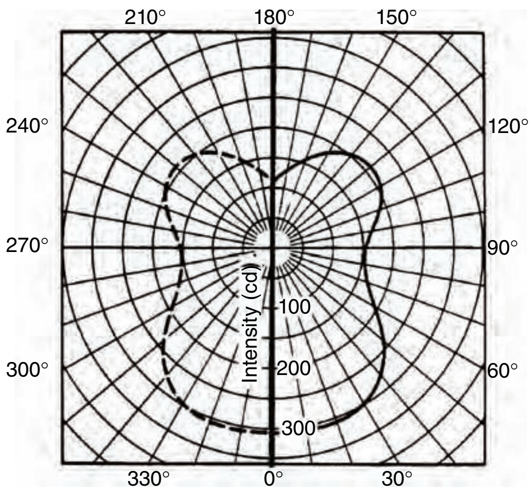


Fig. 13.15 *Typical luminous intensity (cd) distribution curve for a general diffuse-type luminaire. Because the unit is symmetrical about its vertical axis, only one curve need be shown. Furthermore, only the right side of this curve need be shown, due to symmetry.*

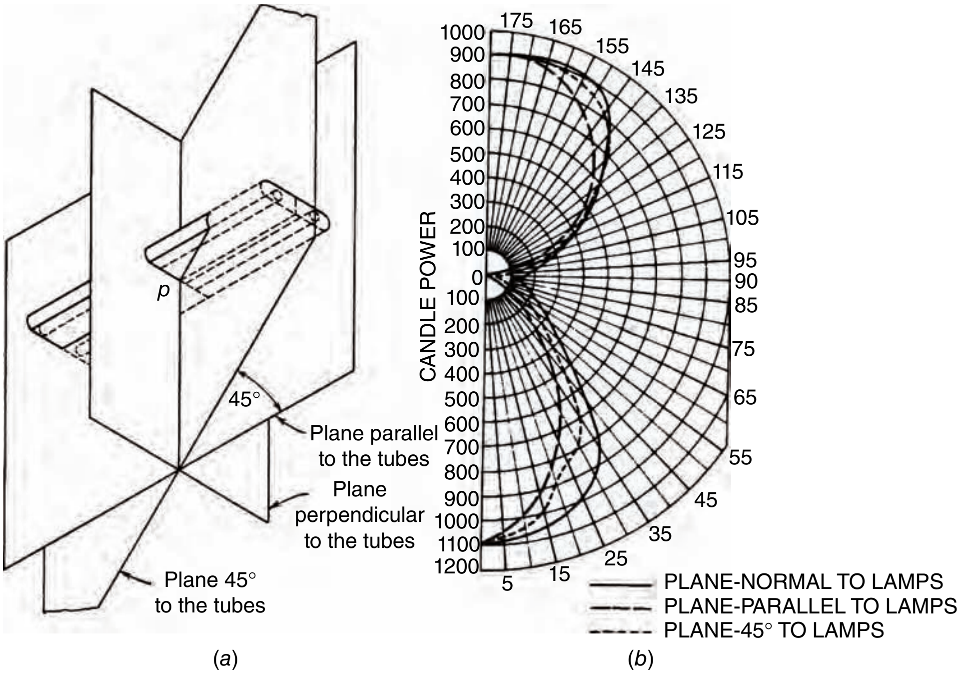


Fig. 13.16 *(a) Due to the asymmetry of a fluorescent luminaire, intensity distribution curves in (at least) three planes are required. (b) Photometric distribution for this fixture is symmetrical in each individual plane; therefore, only one side of a curve is required. By convention, the right side is used.*

then only a single set of values is required, and the resultant plot is valid in all vertical planes through the source. Thus, for incandescent lamps, downlights, open circular reflectors, and the like, only a single CDC is required. For a non-symmetric source such as a fluorescent luminaire, CDC curves in several planes are required to define the fixture's distribution characteristic. Normally, manufacturers will provide longitudinal and crosswise curves, plus a diagonal (45° plane) curve on request. This is illustrated in Fig. 13.16, where the three planes and typical resultant curves are shown.

Most CDC plots are made on polar coordinates because such a plot clearly shows directions and magnitudes. Nevertheless, polar plots tend to crowd near the nadir, and accurate magnitude readings at the cutoff angle are difficult to make. For this reason, it is occasionally desirable to obtain a plot on rectangular coordinates. One such plot is shown in Fig. 13.17. The usefulness of intensity distribution curves will become clear in our subsequent discussions on lighting fixture diffusers, point-by-point calculations, and direct and reflected glare. It should be noted that the area of the CDC curve is *not* a measure of the lumen output.

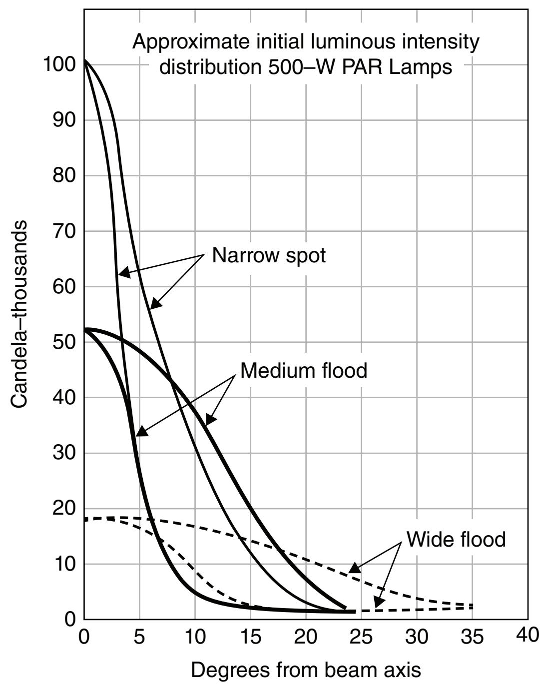


Fig. 13.17 *Luminous intensity distribution curves plotted in rectangular coordinates. Note that candela values near the cutoff angles are easily read, which is not the case in polar plots.*

LIGHT AND SIGHT

13.11 THE EYE

Because any discussion of light and lighting techniques is irrelevant to our purposes unless ultimately related to vision, we turn to a cursory examination of the human eye before proceeding further with discussions of lighting.

Light impinging on the eye enters through the pupil, the size of which is controlled by the iris, thereby controlling the amount of light entering the eye. The lens focuses the image on the retina, from which the optic nerve conveys the visual message by electric impulse to the brain. Figure 13.18 shows the structure of the eye and the parallel structure of a camera.

Light is focused on the retina, which contains in all some 150 million light-sensitive cells of two types: *rod* and *cone* cells. The central portion of the eye, near the fovea, is an area of pinhead size containing about 100,000 cone cells, which accounts for the extreme precision of foveal (center-focus) vision. The cones are responsible for the ability to discriminate detail; they also give us the capacity to perceive color, and are able to detect *luminances in the range 3 to 1,000,000 cd/m²*. Proceeding outward from the fovea, a second type of cell is encountered called a rod cell. Rods can detect luminances from 1/1000 cd/m^2 to approximately 120 cd/m^2 and are extremely light sensitive, giving a response to light 1/10,000 as bright as that required by cone cells. However, rod cells lack color sensitivity, thus accounting for the fact that in dim light (rod vision), we have no color perception and all colors appear as varying shades of gray. Rod cells also lack detail discrimination, making "night vision" quite coarse. Finally, rod cells are slower acting than cone cells and therefore have a low degree of flicker fusion; stated conversely, they are highly motion sensitive. Because these cells occur at the outer portions of the retina, their motion sensitivity results in our being best able to detect movement when looking out of the "corner of the eye." Looking at a 60-Hz fluorescent tube directly and then obliquely demonstrates this effect.

Figure 13.19 is a sketch illustrating the angles involved in the field of vision. Of particular interest is the extreme narrowness of the cone of central (foveal) vision, in which acute perception of detail takes place. This area is so small that your eye must refocus on each dot in a colon (:) if you

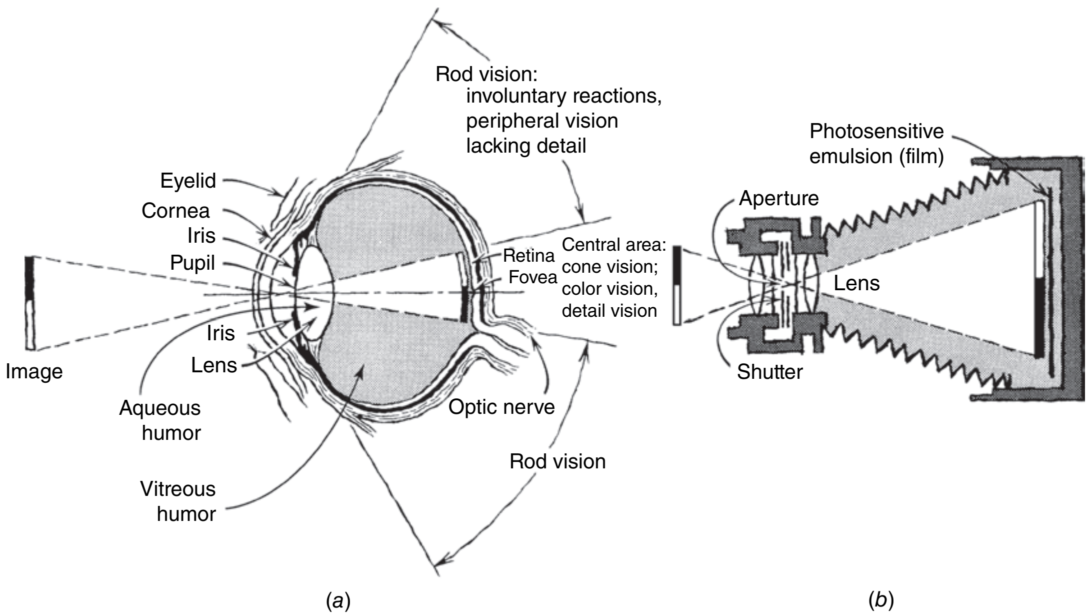


Fig. 13.18 *The human eye (a) and the camera (b) operate on similar optic principles. The cornea acts as an outer refracting lens that introduces light into the iris. The iris and pupil control the f-stop, or opening of the eye, and correspond roughly to a range of f2.1 to f11. The lens, which acts as a perfectly smooth automatic zoom lens, can focus from about 2 in. (50 mm) to infinity.*

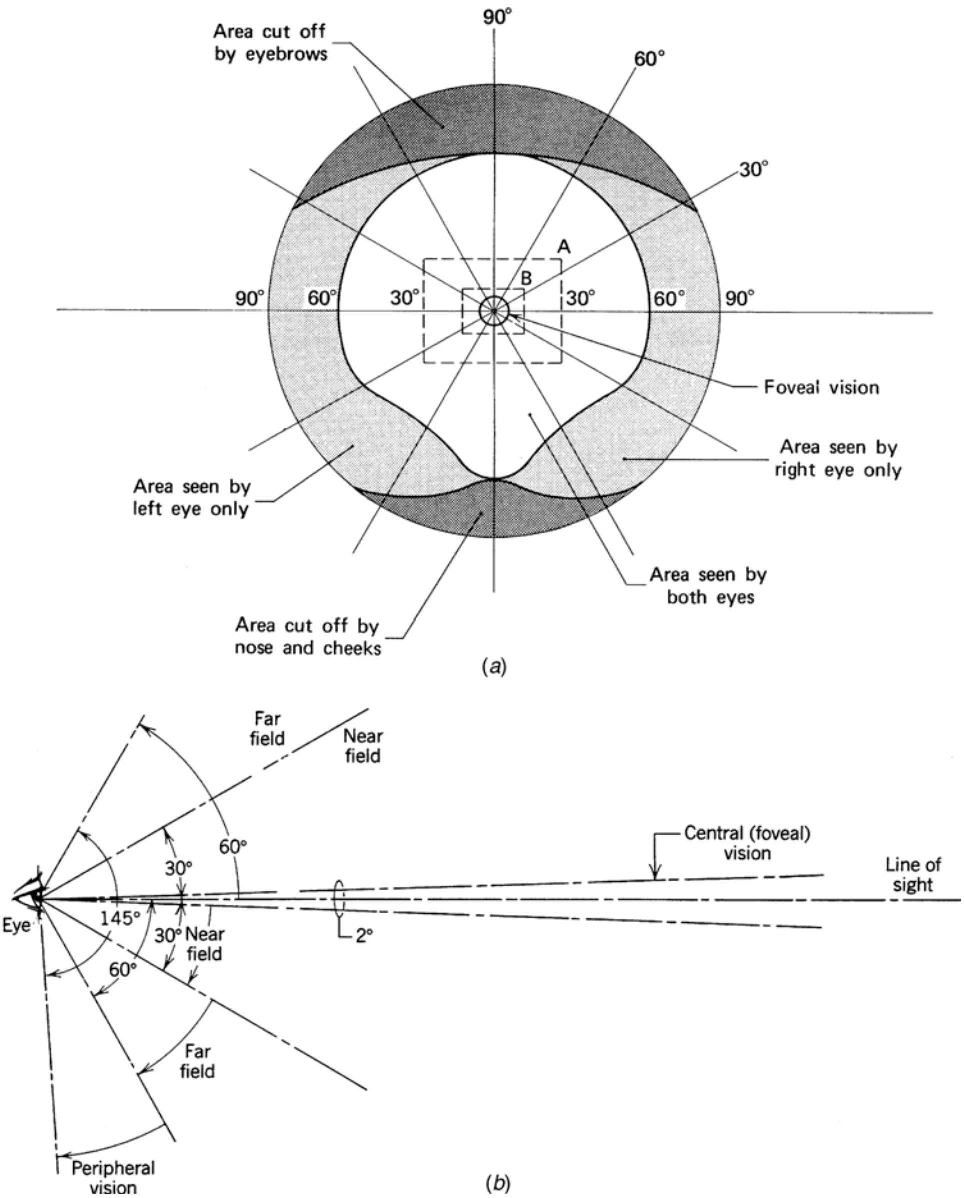


Fig. 13.19 *The fields of vision of a normal pair of human eyes (a) and the subtended angles (b). The rectangles A and B superimposed on the field of vision in (a) represent a large magazine and a small book, respectively.*

wish to examine each individually. Surrounding this central area is a cone of binocular vision of 30° half-angle, called the *near field* or *surround*, in which area most of the coarser sight information is gathered. Beyond this cone we have far-field and peripheral, primarily horizontal, monocular vision. It is the far-field and peripheral areas that largely give us our subjective, ambience-type reactions.

13.12 FACTORS IN VISUAL ACUITY

The three components of any seeing task are: the object or task itself, the lighting conditions, and the observer. The following list gives the variables affecting each of these three components. Based upon the results of many investigations, they can be categorized as of primary or secondary importance.

I. The Task
  Primary Factors
  a. Size
  b. Luminance (brightness)
  c. Contrast, including color contrast
  d. Exposure time—needed or given
  Secondary Factors
  e. Type of object—required mental activity; familiarity with the object (in reading, familiarity is so important as to become the primary factor)
  f. Degree of accuracy required
  g. Task—moving or stationary
  h. Peripheral patterns

II. The Lighting Condition
  Primary Factors
  a. Illumination level (illuminance)
  b. Disability glare
  c. Discomfort glare
  Secondary Factors
  d. Luminance ratios
  e. Brightness patterns
  f. Chromaticity

III. The Observer
  Primary Factors
  a. Condition of the eyes (both health and age)
  b. Adaptation level
  c. Fatigue level
  Secondary Factors
  d. Subjective impressions; psychological reactions

Although in the following discussions these factors are considered individually, many are interrelated. Thus luminance (I*b*) and adaptation (III*b*) result from the presence of illumination (II*a*); subjective impressions (III*d*) are dependent on brightness patterns (II*e*) and chromaticity (II*f*); fatigue (III*c*) results from a combination of many of the factors, and so on.

In the literature, it is common to find reference to the *quantity* and *quality* of the lighting environment. In terms of these factors, the quantity of light has reference to item II*a* and the quality to items II*b* through II*f*.

The basic visual tasks are the perception of low contrast, fine detail, and brightness gradient. Assuming a good lighting environment—that is, low glare, acceptable luminance ratios, and white light plus a normal pair of unfatigued eyes—visual acuity is primarily dependent on items I*a* to I*d*, the interrelated effects of which have been determined by a large number of field tests. Remember that the seeing task under discussion involves foveal vision (i.e., focusing and concentrating on small-area detail). This is a vastly different task than normal reading, where the eye rapidly scans familiar images without focusing on details, and the brain immediately understands even when much of the information is missing, as in poor reading copy. The task discussed next is quite different and could be compared to studying mathematical equations or reading an unfamiliar language or even proofreading spelling. All of these tasks require detailed examination of each symbol individually.

(a) Size of the Visual Object

Visual acuity is generally proportional to the physical size of the object being viewed, given fixed brightness, contrast, and exposure time. Because the actual parameter is not physical size but subtended visual angle, visual ability can be increased by bringing the object nearer the eye (Fig. 13.20). It is assumed that we are dealing with a pair of *young eyes*, because at ages above 40, the accommodation ability of the eye becomes limited and bringing the object closer blurs the focus.

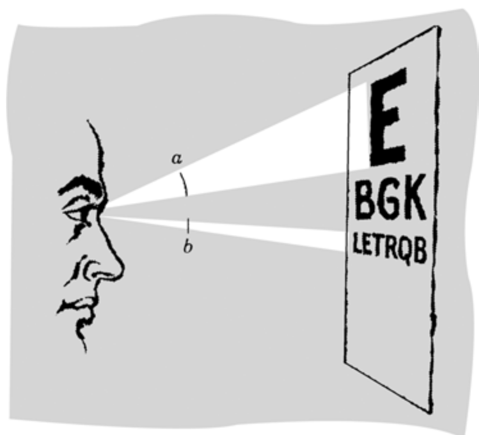


Fig. 13.20 *Relationship between object size and visibility is demonstrated by comparison of subtended angles a and b.*

(b) Subjective Brightness

The sensation of vision, as explained previously, is caused by light entering the eye. This light may be thought of as a group of convergent rays, each ray coming from a different point in space and therefore carrying different visual information. The composite of these rays constitutes the entire visual picture that the eye sees and the brain comprehends. The individual rays differ from each other in intensity and chromaticity, depending on the part of the viewed object from which they were reflected. The intensity of these cones of light determines and describes the perceived brightness of the object being viewed.

The human eye detects luminance over an astonishing range of more than 100 million to 1, the lower levels being accomplished after an adjustment period called *adaptation time*. For dark adaptation, this period varies from 2 minutes, for cone vision, to up to 40 minutes, for rod vision; for light adaptation (going from dark to light), on the other hand, the time lag is much less for both types of vision. The effects of adaptation on apparent (photometric) brightness are discussed in the following section. Tables 13.2 and 13.3 list some measured luminances of everyday visual tasks.

An interesting characteristic of light-level adaptation is a shift in the sensitivity curve of the eye (Fig. 13.6*b*). Whereas for the light-adapted eye (photopic vision) maximum sensitivity occurs at 555 nm in the yellow–green region, the dark-adapted eye (scotopic vision) peaks at 520 nm in the blue–green region. This means that as the light dims, the warm colors—yellow, orange, red—become grayed, and the blues and violets stand out. This phenomenon can be important in the lighting design of restaurants, where light levels generally vary inversely with restaurant quality. Very few foods are blue or violet.

Returning then to the primary consideration of visual acuity as affected by luminance, we can state that, in general, visual performance increases with object luminance. However, a great deal depends on the background against which an object is viewed and the consequent contrast in brightness between the object being viewed and its surroundings.

TABLE 13.2 Typical Luminance Values[a]

Object	Luminance cd/m^2	Luminance Footlamberts
Black glove on a cloudy night	0.0003	0.0001
Wall brightness in a well-lighted office	100	30
A sheet of white paper in an office	120	35
Green electroluminescent lamp	150	45
Asphalt paving—overcast day	1300	380
North sky	3500	1000
Moon, candle flame	4000–5000	1300
Fluorescent tube	6000–8000	2200
Kerosene flame	8500	2500
Hazy sky or fog	15,000	4400
Snow in sunlight	25,000	7300
100-W inside-frost incandescent lamp	50,000	14,600
Sun	2.3 E9	0.67 E9

[a]Values are rounded off.

TABLE 13.3 Preferred and Permissible Luminances

Item	Luminance in cd/m^2
Recommended road luminance	1–2
Minimum discernible, chromatic	2–3
Clearly discernible human features	15–20
Preferred wall luminance	25–150
Preferred ceiling luminance	50–250
Preferred task luminance	100–500
Permissible luminaire luminance (depending on position in field of vision)	1000–7000

(c) Contrast and Adaptation

The discussion that follows assumes full-spectrum white light and ignores the effects of chromaticity, which is considered separately. Many researchers in the area of visibility have concluded that contrast is the single most important factor in visual acuity. This is self-evident when we realize that, in fact, the eye sees only contrast. This can readily be demonstrated by viewing a large, evenly lighted, monochromatic, diffuse-finish surface (preferably white) that encompasses the entire visual field. The eye is unable to focus on such a surface because it sees no contrast, but only a single luminance. Therefore, the eye itself attempts to provide the missing contrast by seeing an internally reflected view of the retina in yellow.

To properly evaluate the effect of contrast (luminance ratio) on visibility, we must first determine the nature of the visual task or, more simply, exactly what it is that we are trying to see. As stated before, the basic visual tasks are detail discrimination and detection of low contrast. Examples of the former are drafting, industrial product inspection, or something as simple as discriminating between the numbers 3, 6, and 8, which are similarly shaped. Detection of low contrast includes reading faint copy, sewing a black fabric with black thread, and the like.

Contrast is a dimensionless ratio, defined as

$$C = \frac{L_T - L_B}{L_B} \text{ or } \frac{L_B - L_T}{L_B} \text{ or } \left|\frac{L_B - L_T}{L_B}\right| \tag{13.7}$$

where L_T and L_B are the luminance of the task and background, respectively, in any units. Thus, C varies from 0 (no contrast) to 1.0 (maximum contrast). In most situations, the illumination on the task and background is the same. Therefore, because luminance is the product of illuminance (lux) and reflectance, contrast can also be expressed as

$$C = \left|\frac{R_B - R_T}{R_B}\right| \tag{13.8}$$

where R_T and R_B are the reflectances of the task and the background, respectively. From this equation, we can conclude that *contrast is generally independent of illuminance* (ignoring specularity).

High contrast is the critical factor in visual appreciation of outline, silhouette, and size, which are the factors involved in the task of reading. Thus, black-on-white print can be read with ease even in moonlight, which is at best 0.1 lux illuminance, because the contrast is so high (94%). An important conclusion can then be drawn about a *reading task*: With high contrast (clear, legible print), visibility is essentially *independent* of illuminance above a certain minimum. Indeed, high illuminance values can be detrimental because they generally go hand in hand with high luminance sources, and these in turn can cause veiling reflections (see Section 13.18).

Now refer to Fig. 13.21. Note that as the contrast between the letters in the word "performance" and the background diminishes, the individual letters become harder to read. The end letters of the word require an illuminance of up to 1000 lux, and that suffices only because we expect the letter *e* at the end. Were it an unknown sign, illuminance

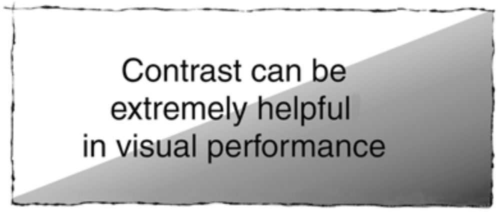


Fig. 13.21 *High contrast is helpful when the seeing task involves detection of silhouette detail.*

of a magnitude of 10,000 lux or more would be needed. These latter letters are an example of the second type of visual task mentioned previously—low-contrast poor copy requiring surface detail study.

The *e* at the end of "performance" in Fig. 13.21 is printed with the same density as the *C* in "Contrast." It exists, and with enough lighting, the negative effect of lack of contrast can be overcome. This is not so with copy from a used-up printer cartridge or a washed-out photocopy. There, the data simply do not exist, and increased lighting only makes this fact more evident.

High background luminance makes an object look darker, and therefore assists in outline detail discrimination, which is precisely the visual task involved in reading. For this reason, black-on-white is desirable for reading. (This is a special case of lateral adaptation, which is discussed in Section 13.25.) Conversely, high background luminance makes surface examination more difficult. A simple experiment demonstrates this effect. Stand near a window and hold your hand in front of you with the floor as background. The skin surface detail is perfectly clear—in rough proportion to its luminance. Now hold your hand up against the window with the daytime sky as background. The hand outline is clear, but the skin surface appears dark—the brighter the sky, the darker the skin surface. The reason for this is that the eye automatically adapts to the average brightness of the entire scene.

It is well known that when using an automatic exposure control camera to photograph a dark object on a light background (such as a person in a snow scene) it is necessary to manually increase the camera aperture in order to obtain additional light to photograph the detail of the darker object. (In doing this, we overexpose the rest of the scene.) Because we cannot easily control the aperture of our eyes, we must compensate for the detrimental effect of high background luminance in another way—for example, by increasing the surface luminance of the visual task. Indeed, this method is frequently employed (see Section 13.20*b*). Limited visual compensation can be made by squinting; this reduces the field of vision and the overall scene brightness. For maximum visual acuity, *the luminance of a surface-type task should be the same as, or slightly higher than, that of the background*, but ratios of 3:1 are acceptable in most circumstances.

Another way of understanding this is to consider the adaptation characteristic of the human eye (Fig. 13.22). As stated, the eye adapts to the brightness level of the *overall* scene and sees each object in the scene in the framework of that adaptation level. Thus, at an adaptation level of 1 fL (3.4 cd/m^2), a measured luminance ratio of 1:10 (horizontal scale on Fig. 13.22) appears to be only approximately 1:4 (vertical scale); that is, the apparent ratio is *smaller* than the actual one. Put another way, the low level of eye adaptation causes the eye to diminish the difference between high brightnesses. This effect becomes smaller as the adaptation level rises, until at an adaptation level of 1000 fL (3400 cd/m^2) (daylight conditions), the apparent and actual ratios correspond; that is, smaller ratios are recognizable. Because visual acuity is, by definition, the ability to distinguish between different levels of luminance, we have in effect demonstrated that *visual acuity increases with increased adaptation level*.

The second important conclusion that can be drawn is that at high adaptation levels, apparent brightness is lower than actual brightness, and vice versa. Thus, a shadowed object near a window looks *darker* than it actually is; contrary to first expectation, it must be better lighted than a similar object further inside the room for equal visibility. That this effect (high-level adaptation) is primarily important in daylight situations is also apparent from the curves. At a 100-fL (340-cd/m^2) adaptation level, which is approximately that of a brightly lit interior space, apparent and actual luminance levels coincide. The reverse effect, resulting from low adaptation levels, can be very important in design situations where low lighting levels are found, such as theaters, lecture halls, restaurants, and storage spaces. Sources of light that would be entirely acceptable at a higher adaptation level can easily become an annoying glare

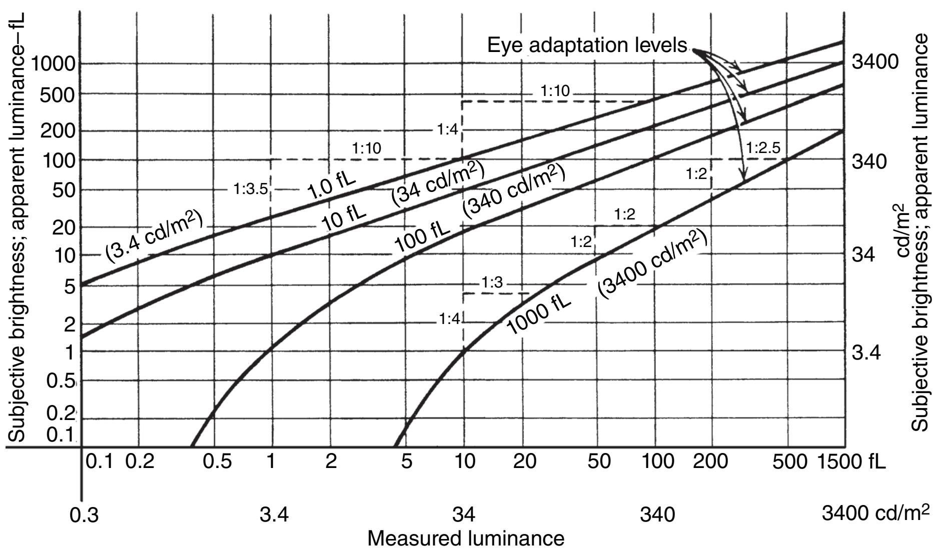


Fig. 13.22 *The effect of an eye's adaptation level on perceived (subjective) brightness is clearly shown. (Adapted from H. Cotton. 1960.* Principles of Illumination. *John Wiley & Sons. New York.)*

source at a low adaptation level. Good examples are a theater usher's flashlight or the blinding glare of an oncoming car's headlights.

The foregoing discussion of contrast deliberately avoided any discussion of *object* colors and the effect of color contrast on visual acuity for several reasons:

- Office-type tasks (paperwork) are most often black-on-white tasks.
- Most work tasks involving colored objects deal with unsaturated colors, where the pronounced effects of color contrast are minimal.
- The effect of object color on visual acuity is very complex because it involves the color characteristic not only of the object, but also of the background and the surround plus the chromaticity of the illuminant.

That being said, we must, however, at least mention a number of important object color phenomena that bear on visual acuity.

- The subjective brightness of a colored (heterochromatic) object is greater than that of an achromatic object for the same photometric luminance. This effect varies with hue and saturation. It is more pronounced with saturated colors than with those of low chroma, and more in the blue–purple–red area than the yellow–green area.
- Colored objects on a dark-to-black background appear light and desaturated. Conversely, colors on a light-to-white background appear darker and more saturated.
- Adjacent complementary colors produce a pale-to-white border between them. The effect also appears when the task and background colors are complementary, and is most pronounced with saturated (high-chroma) colors.

These remarks deal with *object* color only. As stated at the beginning of this section, we are assuming white, full-spectrum light, so that neither object color nor visual acuity is affected. Effects on visual acuity resulting from unbalanced illuminants, such as those from high-pressure sodium lamps and, to a lesser extent, from halide and fluorescent sources, are the subject of intensive and ongoing research. Some of the results are adduced in the discussion of illuminant chromaticity at the end of this chapter. These effects are most pronounced, and therefore most important, in relation to elderly persons and persons with visual defects. We must again, therefore, emphasize that unless otherwise specifically stated, our discussions of vision, light, and lighting assume full-spectrum white light and young, healthy eyes.

(d) Exposure Time

Registering a meaningful visual image is not an instantaneous process, but one that requires finite amounts of time. Just as a photograph can be taken in dim light by using a longer exposure, so can the human eye better distinguish and discriminate fine detail in poor light given time (and neglecting eyestrain). Of course, the time needed depends on the type of task, but the principle of shorter time at higher illumination, within limits, remains the same. This is particularly true when the object being viewed is not static but is in motion.

The phenomenon, however, is not linear. For one specific task tested, increasing the luminance by a factor of 6 halved the seeing time, whereas a further sixfold increase in luminance reduced the time only another 20%. Thus, as in the case of improved contrast with increasing background brightness, we have a case of diminishing returns.

With the parameter of time, as with other parameters of visual acuity, the same qualification applies. When dealing with material that does not require detail discrimination, improved performance does not necessarily result from improved illumination. It has been amply demonstrated that speed of reading and comprehension are substantially independent of illumination levels above a minimum, but are very much dependent on the contrast quality of the material.

(e) Secondary Task-Related Factors

Refer again to the list of factors in visual acuity in Section 13.12. We have discussed at some length the primary task-oriented factors I*a*–*d*, and at this point wish to consider secondary factors *e*–*h* of that list. These items refer essentially to the level of concentration required. Thus, spray painting a large metal object or packing fruit are very different from inspecting the painted object for defects or the fruit for bruises. The former tasks are largely mechanical and repetitious, whereas the latter tasks require continuous judgmental decisions based on visual information. Because both of the latter tasks are frequently moving (assembly-line type of work) and both involve penalties for inaccuracy (rejection at a later inspection state or negative feedback from the purchaser), the lighting required for these tasks is several orders of magnitude better than that for related but largely mechanical tasks. Indeed, extrapolation from laboratory condition tests yields only a range of lighting recommendations. Thereafter, considerable field testing and adjustment are required.

An observer performing a lab test has a different level of concentration and performance than that of a person at an 8-hour-a-day task. The latter compensates for an unsatisfactory seeing condition by:

1. Moving the work to a better viewing angle
2. Moving the head and eyes to a more comfortable position
3. Reducing the distance between the eyes and the task to the extent that the eyes can accommodate
4. Complaining about a poor-contrast task so that something is done about it (such as fixing the photocopying machine)
5. Taking more time to perform the seeing task involved (which, if it affects production, frequently spurs management to make appropriate alterations in the work environment)

The last item in the task list—peripheral patterns—deals with the visual surround rather than the immediate area of the work. Other than glare sources, which are discussed separately, there are many items that, although outside the central field of vision, can disturb the viewer's concentration and therefore the task performance of a worker. These include movement (vehicles, machines, persons), to which peripheral vision is particularly sensitive; large variations in the brightness pattern of the background caused by such activities as periodic opening of an outside door or welding; and even nonvarying patterns that are disturbing because of their very nature, such as checkerboard light-dark patterns, or devices on which it is difficult to focus the eyes, such as crossed patterns of wires and bars. None of these items is strictly lighting-oriented, but they are noted here to demonstrate that an adequate lighting design necessarily includes adjustments for particular field conditions.

(f) Observer-Related Visibility Factors

It is a well-documented fact that the visual performance of *healthy* eyes decreases with age. This reduction is demonstrated principally in two areas: an increase in minimum focusing distance caused by increasing lens rigidity and a decrease in sensitivity caused by clouding of the cornea, lens, and vitreous humor. Both of these effects can be compensated for, the former with external lensing (eyeglasses) and the latter by increased task size, luminance, contrast, and exposure time, as explained previously. The point is, of course, that the age of the worker is an important parameter in the vision equation.

Furthermore, maximum performance may not be synonymous with maximum comfort or minimum fatigue. Indeed, the reverse may sometimes be true. Most experts agree that what is normally referred to as *eyestrain* is a condition of the eye muscles resulting from extensive and intensive eye use. Thus, excellent performance under excellent lighting conditions can still produce fatigue because of the demanding nature of the task. In addition, as discussed later, discomfort glare or even excessive lighting can cause fatigue without affecting performance.

The lighting designer must be concerned not only with providing adequate and appropriate lighting levels, but also with all of the factors involved. Many, indeed, are beyond his or her control. Some, such as task contrast, previously thought to be outside the lighting designer's province, should be examined by the designer in an overall "lighting, plus task, plus observer" problem context, in order to make recommendations. Acceptance of these recommendations is a client decision.

Recent work in field testing of visibility in real-work situations considers all of these parameters in arriving at a visibility judgment. The entire field of visibility and visual performance is undergoing very active and continuing research. Definitive answers to the elusive question of how to design for optimal viewing have not yet been found. Various parameters and criteria for judging aspects of visibility have, however, been slowly established over the years. These include: *equivalent spherical illumination* (ESI), which is a contrast-related visibility criterion; *relative visual performance* (RVP), which rates a vision situation in terms of speed and accuracy of performance; *visual comfort probability* (VCP), which judges the visual comfort of an overall scene; and a somewhat ephemeral and entirely subjective impression called *visual clarity*. Other research has concentrated on the relationship between eye pupil size and visual acuity and, based on results from this research, the relationship between pupil size and various aspects of light and lighting. What has been confirmed to date is the complexity of human work-oriented vision, as well as our inability thus far to adequately quantify the interrelationships among the many factors involved—quantification being the basis of reliable, replicable design.

(g) The Aging Eye

The past few decades have seen a remarkable increase in human life expectancy in modern Western countries, resulting in a sharp increase in the aged population. In the United States, at the time of this writing, 13.7% of the population is above 65 years of age (U.S. Census Bureau)—a proportion that is expected to reach 20% by the year 2020. As a result, lighting design must take cognizance not only of special requirements in buildings specifically intended for use by the aged but also, increasingly, in general-use public buildings. To this end, a brief review of these special requirements is presented here.

Refer to Fig. 13.18. Light enters the eye through the cornea, passes through the aqueous humor, and enters the lens through the pupil. After being focused by the lens, it continues through the vitreous humor and finally projects the viewed image, reversed, on the retina. As the eye ages, a whole spectrum of physiological changes may occur; some are usual and are therefore classified as normal; others, such as cataracts, are less common but are still considered by ophthalmologists to be an expected development. Unusual biological developments (which are medically classified as *pathologies*), being only indirectly or partially related to aging, are considered outside the purview of normal lighting design. Expected biological developments, on the other hand, being directly linked to aging, are considered within the scope of normal lighting design. The characteristics of such expected developments, and their influence on said field of design, are briefly described in the following subsections.

Cornea. This perfectly clear outer lens tends to become cloudy, with corresponding reduction of visual clarity and acuity. This results in a requirement for more light to overcome the reduction in light intensity on the retina. The overall effect is very similar to that of a neutral density filter on a camera lens, the difference being that such a filter is most often used to reduce excessive ambient light without excessively reducing the shutter opening (increasing the *f*-stop). The need for additional light for aging eyes is recognized in most modern systems of illumination specification.

Lens. The lens, which begins life as a very-lightly-yellow-tinted, flexible crystalline body, gradually thickens and darkens in tone. As a result of the thickening, flexibility is reduced, resulting in the well-known inability to focus on objects that are near (presbyopia or hyperopia). The yellowing both reduces the overall light intensity in the eye and selectively filters the blue portion of the spectrum. Research seems to indicate improved visual acuity through pupil size control when the incident light is rich in the blue area of the spectrum. Because lens yellowing *reduces* the blue frequencies, the overall effect is again the requirement of additional light to achieve desired visual acuity.

A second and more important degenerative phenomenon of the lens is its gradual clouding. When the opacity is confined to the perimeter, its effect is negligible because vision is unaffected. When small, opaque areas appear within the visual axis through the lens, vision is affected in two ways:

1. The viewed image is dimmed and blurred due to opacities in the field of view.
2. Light entering the lens is scattered by interreflections from the opaque particles, resulting in a subjective impression of glare. This effect is particularly severe outdoors, where light enters the lens from all angles.

The net result of these reactions is a requirement for more light, but an even more pressing requirement that sources of glare and peripheral light be eliminated. (People with this condition frequently wear eyeglasses and sunglasses with large, opaque side shields to block peripheral light and thus reduce glare.) Also, because short-wavelength (blue) light interreflects and scatters more readily than does long-wavelength (yellow–red) light, such persons are more comfortable with incandescent sources and low color-temperature fluorescent lamps (2700–3100° K) than with sources rich in the blue–green spectrum. (Ophthalmologists frequently prescribe yellow-tinted eyeglasses for people with this lens condition in order to filter out blue light.)

Finally, a less common but still prevalent condition of the aging lens is the development of fluorescent particles, called *fluorigens*, in the vision path. In the presence of UV radiation (as exists in daylight), and fluorescent as well as high-intensity discharge (HID) sources, these particles fluoresce—causing scatter, blur, and glare. The solution to this problem is a combination of yellow-tinted eyeglass lenses and a reduction of light sources containing appreciable quantities of UV.

Pupil. The pupil controls the amount of light entering the eye and is therefore intimately involved in the constantly changing accommodation level of the eye. The pupil muscles react more slowly as they age, thus lengthening accommodation time. Dark-to-light accommodation is very rapid in the young eye, and is barely noticed except for extreme changes, such as exiting a cinema into sunlight. With an aging eye, the slower pupil results in severe glare sensations with even small brightness changes.

The net result of all the normal changes taking place in the aging eye is a heightened sensitivity to glare, intolerance to the blue–UV end of the spectrum, and an overall requirement for higher illuminance levels. For the lighting designer, these needs translate into requirements for very careful selection and placement of luminaires, increased use of indirect lighting, and particular attention to the spectrum of the light sources used. Because some of these requirements are not only mutually incompatible but also contrary to energy-efficient design practices, it may be particularly difficult to satisfy all the requirements in spaces occupied by persons with a wide range of ages. In work areas of this type, it may be wise to provide for the possibility of readily changing lighting conditions in a limited area to accommodate older occupants, keeping in mind the glare and color factors discussed previously.

QUANTITY OF LIGHT

13.13 ILLUMINANCE LEVELS

Returning to the list of factors in Section 13.12, and having discussed the task-oriented and observer-oriented items (except for psychological reactions, which is covered in Section 13.25), we turn now to item II, the *lighting condition*. This is frequently, if somewhat inaccurately, divided into two groups—quantity and quality of lighting—with item II*a* representing quantity and items II*b* to II*f* representing quality. That such a division is not accurate becomes clear in our discussion of glare in Sections 13.17 to 13.20.

An understanding of the factors involved in visual acuity, as discussed previously, does not answer the most basic lighting design question, which is: "How much light must I provide for the specific visual task at hand?" That this question is extremely difficult to answer is evidenced by the fact that, even today, recommendations for similar tasks vary by ratios as high as 10:1 among countries with highly developed technologies. Because this is an unsatisfactory situation in an era of global markets, international construction, and international cooperative lighting research, the trend since the late 1980s has been to attempt a degree of standardization.

The North American (IESNA) recommendations were originally developed analytically by extrapolation from extensive laboratory tests. The function of these tests was to determine the conditions under which small differences in contrast could be detected for specific degrees of accuracy, with variable parameters of task luminance, size, and exposure time. The idea behind the tests was that visual acuity could be defined as the ability to distinguish differences in contrast.

In addition, because of the moral and legal pressure for energy conservation (ANSI/ASHRAE/IESNA Standard 90.1 is mandated by many codes), IESNA has taken additional steps toward the rationalization of its very influential illumination standards. They include recognition of fatigue and task familiarity (e.g., reading) as factors in determining illuminance levels, in establishing lighting power budgets, and in setting energy standards that encourage both the use of daylight as a normal component of a space's illumination and the utilization of task/ambient lighting design as the preferred technique wherever high levels of task lighting are required.

13.14 ILLUMINANCE CATEGORY

Before discussing illuminance recommendations, it is necessary to understand the basis of their derivation, applicability, and shortcomings. As noted in the preceding section, most of the IESNA task illuminance recommendations are derived by extrapolation from threshold contrast visibility tests that yield a required task luminance. Assuming uniform, diffuse task reflectance and uniform illuminance, it is then a simple step to calculate required illuminance, since luminance is simply the product of illuminance and reflectance. In SI units,

$$L = \frac{E \times RF}{\pi}$$

and in I-P units,

$$fL = fc \times RF$$

where

L = luminance in cd/m^2

E = illuminance in lux

RF = reflection factor

fL = luminance in footlamberts

fc = illuminance in footcandles (see Example 13.4 and Fig. 13.7)

A number of reservations about this method have been voiced by respected authorities. One is based on research that indicates that suprathreshold visibility requirements are more readily related to eye brightness adaptation levels than to threshold contrast luminance levels (see Fig. 13.22 and the associated text discussion). Another objection is that deriving suprathreshold luminances from threshold values remains dependent on applied criteria, and can therefore vary considerably. Still another objection is based on the readily demonstrable fact that the sensation of vision is not mathematically related to photometric luminance. (For instance, a black surface of 10% reflectance, illuminated with 900 lux, and a white surface of 90% reflectance, illuminated with 100 lux, both have exactly the same luminance—yet the eye always sees the white surface as lighter than the black one by a large margin.) In essence, all of these reservations add up to a cautioning that IESNA illuminance recommendations are meant to serve as a consulting voice for, not as the set-in-stone doctrine of, overall lighting design.

Returning to said recommendations—visual task studies indicate that, assuming good contrast, the required luminances, categorized by type of task, are roughly as follows:

Category of Visual Task	Required Luminance (cd/m^2)
Causal	10–20
Ordinary	20–100
Moderate	100–200
Difficult	200–400
Severe	Above 400

The dependence of required illuminance upon task reflectance (RF) can be seen by a glance in the following tabulation, which shows quantitatively the illuminance requirements in the previous categories for tasks of radically different reflectance.

Category of Visual Task	***Required* E (*lux*)[a]**	
	RF = 50%	***RF = 10%***
Casual	62–125	300–625
Ordinary	125–625	625–3125
Moderate	625–1250	3125–6250
Difficult	1250–2500	6250–12,500
Severe	>2500	>12,500

[a]Lux figures rounded.

This illustrates that a single illumination scheme is often inadequate for an area containing widely differing visual tasks. Note that a 10% RF makes all tasks difficult, and that casual seeing comprises only outline recognition.

13.15 ILLUMINANCE RECOMMENDATIONS

Illuminance recommendations provide guidance for sufficient illuminance for a range of tasks or appropriate surface luminances in a space. Illuminance recommendations are consensus values gathered from scientific research, experience, available technology, economic considerations, best practice, and energy concerns. They should be used only in conjunction with other relevant lighting criteria (e.g., illuminance uniformity, modeling, color, glare control). Recommendations often form part of lighting design criteria or specifications and codes, so the intent is to provide validated guidance. The recommendations in this section are expressly for North America. Many countries and/or regions have their own published lighting standards. Any specific project should follow the recommendations in force in the project locale.

Three factors are used to determine the recommended illuminances: task characteristics, task importance (described in Section 13.14), and observer characteristics ("visual age" of the observers). IESNA provides illuminance targets (Table 13.4) as a matrix organized with these characteristics in mind. The core illuminance ranges span from 0.5 to 20,000 lux (5 to 2000 fc) in groups of low-level, primarily exterior lighting applications (Categories A–H) to higher-level, primarily interior applications (Categories J–W).

Table 13.4 also reflects the task's inherent potential contrast, size, reflectance, and the importance of speed and accuracy. The observers are estimated to be between 25 and 65 years old. IESNA states that if more than 50% of the occupants are more than 65 years old, the illuminance recommendations are doubled. Typical applications and task characteristics add another layer of refinement, depending on activity, social situations, or cognitive tasks.

For a space with several tasks of varying visual difficulty, the designer is expected to design the lighting and controls so that task requirements are met without overlighting. Overlighting often results when a uniform layout keyed to the most light-intensive task is employed; this outcome, being incredibly inefficient and energy wasteful, is strongly discouraged.

Recommended IESNA illuminance values are *not* applicable to installations in which a visual task is not the deciding factor. Such installations include merchandising spaces, displays of all sorts, theatrical and artistic lighting, mood lighting, safety lighting, light used as part of an industrial process, and so on. Code requirements supersede these recommendations.

For more specificity, IESNA's *The Lighting Handbook* includes a robust range of recommendations for illuminances and uniformities for users to perform various tasks and functions in a wide range of applications and buildings, such as educational facilities, health-care facilities, hospitality and entertainment venues, libraries, manufacturing facilities, offices, residences, retail spaces, sports and recreation venues, transportation facilities, and places of worship. Both analytic and quantitative lighting criteria and a detailed user's guide offer the designer assistance on developing appropriate lighting solutions. Typically, consulting such tables is just the beginning; a large amount of time is usually dedicated to analyzing the depth and breadth of information developed by the design team.

Lighting plays an important role in the use and enjoyment of libraries. Table 13.5 includes a sample of the IESNA illuminance recommendations for a library: targets for horizontal surfaces (E_h) and vertical surfaces (E_v) are organized by task and visual ages of the observers. As a program develops and the design becomes more detailed, thought must be given to more specific aspects of the visual environment. For example, the circulation desk must be visible by library patrons as well as providing visual interest for the general public; the library staff must be able to see certain areas of the library without glare. These kinds of details need to be studied in concert with these foundational recommendations.

TABLE 13.4 Recommended Illuminance Targets

Category		Recommended Illuminance Targets lux (fc) — Visual Ages of Observers (years) where at least half are: <25	25 to 65	>65	Some Typical Application and Task Characteristics
INTERIOR and EXTERIOR applications	A[a]	0.5 (.05)	1 (0.1)	2 (0.2)	Dark adapted situations
	B[a]	1 (0.1)	2 (0.2)	4 (0.4)	Basic convenience situations Very-low-activity situation
	C[a]	2 (0.2)	4 (0.4)	8 (0.7)	Slow-paced situations Low-density situations
	D[a]	3 (0.3)	6 (0.6)	12 (1.1)	Slow-to-moderate-paced situations
	E[a]	4 (0.4)	8 (0.7)	16 (1.5)	Moderate-to-high-density situations
	F[a]	5 (0.5)	10 (1)	20 (2)	Moderate-to-fast-paced situations
	G[a]	7.5 (0.7)	15 (1.4)	30 (3)	High-density situations
	H[a]	10 (1)	20 (2)	40 (4)	Some indoor very subdued circulation situations Some indoor social situations
INTERIOR and EXTERIOR	I[a]	15 (1.4)	30 (3)	60 (6)	Congested and significant outdoor intersections, important decision-points, gathering places, and key points of interest Some indoor social situations Some indoor commerce situations
INTERIOR and exterior applications	J[b]	20 (2)	40 (4)	80 (8)	Some outdoor commerce situations
	K[b]	25 (2.5)	50 (5)	100 (10)	Some indoor social situations
	L[b]	37.5 (3.5)	75 (7)	150 (15)	Some indoor commerce situations
	M[b]	50 (5)	100 (10)	200 (18.58)	
	N[b]	75 (7)	150 (15)	300 (30)	
	O[b]	100 (10)	200 (20)	400 (40)	
	P[c]	150 (15)	300 (30)	600 (60)	Some indoor social situations Some indoor education situations Some indoor commerce situations Some indoor sports situations
	Q[c]	200 (20)	400 (40)	800 (80)	Some indoor education situations
	R[c]	250 (25)	500 (50)	1000 (100)	Some indoor commerce situations
	S[c]	375 (37)	750 (75)	1500 (150)	Some indoor sports situations Some indoor industrial situations
	T[d]	500 (50)	1000 (100)	2000 (200)	Some sports situations
	U[d]	750 (75)	1500 (150)	3000 (280)	Some indoor commerce situations
	V[d]	1000 (100)	2000 (200)	4000 (380)	Some indoor industrial situations
	W[e]	1500 (150)	3000 (280)	6000 (560)	Some sports situations Some indoor industrial situations Some health care procedural situations
INTERIOR applications	X[e]	2500 (235)	5000 (470)	10000 (930)	Some health care procedural situations
	Y[e]	5000 (470)	10000 (930)	20000 (1860)	

Source: Illuminating Engineering Society of North America, *The Lighting Handbook*, 10th ed. © 2011; used with permission. The I-P unit soft conversions were developed by the authors of this book.

[a]Orientation, relatively large-scale, physical (less-cognitive) tasks—Visual performance is typically not work-related, but related to dark sedentary social situations, senses of safety and security, and casual circulation based on landscape, hardscape, architecture, and people as visual tasks.

[b]Common social activity and large and/or high-contrast tasks—Visual performance involves higher-level assessment of landscape, hardscape, architecture, and people and can be work related.

[c]Common, relatively small-scale, more cognitive or fast-performance visual tasks—Visual performance is typically daily life- and work-related, including much reading and writing of hardcopies and electronic media consecutively and/or simultaneously.

[d]Small-scale, cognitive visual tasks—Visual performance is work- or sports-related, close and distant fine inspection, very small detail, high-speed assessment and reaction.

[e]Unusual, extremely minute and/or life-sustaining cognitive tasks—Visual performance is of the highest order in respective fields of health care, industrial, and sports.

TABLE 13.5 Library Facility Illuminance Recommendations

		Recommended Maintained Illuminance Targets Lux (fc)							
		Horizontal (E_h) Targets				***Vertical (E_v) Targets***			
		Visual Ages of Observers (years) where at least half are				***Visual Ages of Observers (years) where at least half are***			
Application and Tasks	**Notes**	**Category**	**<25**	**25–65**	**>65**	**Category**	**<25**	**25–65**	**>65**
Book Lending – Book Stacks									
General[a]	E_h @ floor of book stacks proper	O	100 (10)	200 (20)	400 (40)				
Shelving @ 2′6″ (760 mm) AFF[a]	E_h and E_v @ front face of shelving	P	150 (15)	300 (30)	600 (60)	O	100 (10)	200 (20)	400 (40)
Lending Desk									
Self-service[a]	E_h @ 2′6″ (760 mm) AFF; E_v @ 5′ (1.5 m) AFF	P	150 (15)	300 (30)	600 (60)	M	50 (5)	100 (10)	200 (20)
Staffed[a]	E_h @ 2′6″ (760 mm) AFF; E_v @ 5′ (1.5 m) AFF	R	250 (25)	500 (50)	1000 (100)	O	100 (10)	200 (20)	400 (40)
Periodicals									
Shelving @ 1′0″ (305 mm) AFF	E_v @ front face of shelving					M	50	100 (10)	200 (20)
Computer Center[a]	CSA/ISO Type I and II positive polarity screens. E_h @ 2′6″ (760 mm); E_v @ 4′ (1.2 m) AFF	P	150 (15)	300 (30)	600 (60)	M	50 (5)	100 (10)	200 (20)
Reading Areas									
Grand Reading Room[a]	E_h @ 2′6″ (760 mm) AFF; E_v @ 4′ (1.2 m) AFF	R	250 (25)	500 (50)	1000 (100)	O	100 (10)	200 (20)	400 (40)
Stack Reading Areas[a]	E_h @ 2′6″ (760 mm) AFF; E_v @ 4′ (1.2 m) AFF	R	250 (25)	500 (50)	1000 (100)	M	50 (5)	100 (10)	200 (20)
Study Carrels[a]	E_h @ 2′6″ (760 mm) AFF; E_v @ 4′ (1.2 m) AFF	R	250 (25)	500 (50)	1000 (100)	O	100 (10)	200 (20)	400 (40)
Tables and Chairs[a]	E_h @ 2′6″ (760 mm) AFF; E_v @ 4′ (1.2 m) AFF	R	250 (25)	500 (50)	1000 (100)	O	100 (10)	200 (20)	400 (40)
Special Collections									
Archival Storage	E_h and E_v @ 3′ (910 mm) AFF	P	150 (15)	300 (30)	600 (60)	M	50 (5)	100 (10)	200 (20)
Rare Books	E_h and E_v @ 3′ (910 mm) AFF	P	150 (15)	300 (30)	600 (60)	M	50 (5)	100 (10)	200 (20)

Source: Illuminating Engineering Society of North America, *The Lighting Handbook*, 10th ed. © 2011; used with permission. The I-P unit soft conversions were developed by the authors of this book.

[a]Combination of daylighting and electric lighting strategies can be employed to achieve target values during daylight hours. Daylighting may require unconventional approaches.

QUALITY OF LIGHTING

13.16 CONSIDERATIONS OF LIGHTING QUALITY

Quality of lighting is a term used to describe all of the factors in a lighting installation not directly connected with quantity of illumination. If two identical rooms are lighted to the same *average* illuminance, one with a single bare bulb and the other with a luminous ceiling, there is a vast difference in the two lighting systems. This difference is in the *quality* of the lighting, a term that describes the overall scene—that is, the luminances, diffusion, uniformity, and chromaticity of the lighting.

Excessive luminances and/or excessive luminance ratios in the field of vision are commonly referred to as *glare*. The quality of a lighting system must include consideration of the visual comfort of the system—which is primarily determined by the absence of glare. Glare that is caused by light sources within the field of vision is known as *direct glare*; glare that is caused by the reflection of a light source in a viewed surface is known as *reflected glare* or *veiling reflection* (see Fig. 13.23). The severity of glare is usually expressed through the classifications of discomfort, disability, and blinding glare.

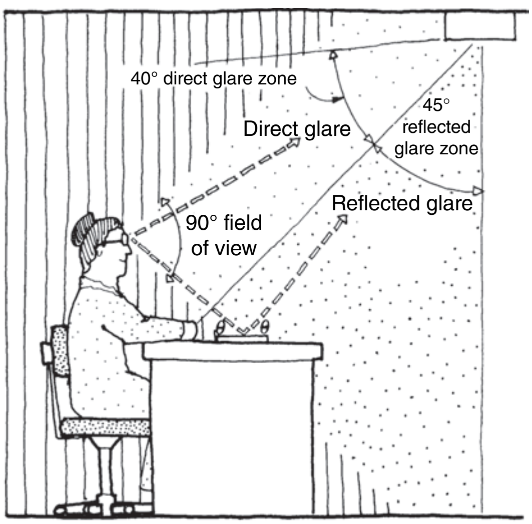


Fig. 13.23 *Glare zones. Direct glare presupposes a head-up position, whereas reflected glare assumes eyes down at a reading angle.*

Factors affecting the severity of glare are: the adaptation level of the eyes, the apprehended size of the glare source, luminance ratios, room size and surface finishes, and the size and position of lighting fixtures and windows. Light sources in the far-field and peripheral-vision areas beyond the central 90° cone are less troublesome as glare sources.

13.17 DIRECT GLARE

The factors involved in producing direct glare are the luminance, size, and position of each light source within the field of vision, plus the adaptation level of the eye. The discomfort of direct glare stems from two facts: First, the eye adapts (rapidly) to the average brightness of the overall visual scene; second, the eye is attracted to the highest luminance in that scene. (The latter fact is used effectively in merchandising displays.) Thus, if an area of high brightness, such as a window or a lighting fixture, exists in the visual scene, and we are looking at an area of lower brightness, such as a work task, three visually disturbing things occur:

1. The eye adapts to a higher luminance level, thus effectively reducing the subjective brightness of the task—essentially making it harder to see what we are looking at (see Fig. 13.22). This is readily demonstrable by alternately blocking and unblocking a direct glare source with one's hand while trying to perform a moderately difficult visual task—there will be an immediate improvement in visibility when the glare source is obscured.
2. The eye is drawn simultaneously in two directions: involuntarily to the source of high luminance, and intentionally to the object we are looking at. The resultant tension causes considerable visual discomfort.
3. The adaptation level is continuously varying as the eye is drawn to the glare source and away again.

Glare is proportional to a source's luminance and its apprehended solid angle. Therefore, a small, bright source is usually not a problem, whereas a large, low-brightness source (such as a luminous ceiling) may be. Indeed, a small, bright source adds sparkle to the field of vision, and many observers find it a pleasant addition in a monotonous lighting environment.

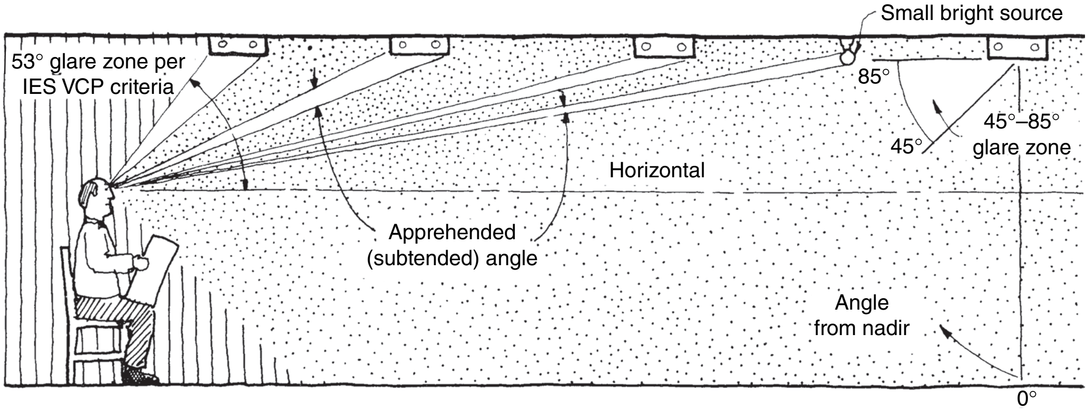


Fig. 13.24 *Determination of direct glare. The glare contribution of each source depends on its size (subtended or apprehended solid angle), luminance, and location in the field of view. Note that the apprehended solid angle of a small source is such that even with high luminance, it is not objectionable. Such sources are normally called sparkle. Glare is much more objectionable with a dark background than with a light one; therefore, light-colored paints on ceilings and upper walls are recommended.*

Although discomfort glare from a scene is cumulative, source luminance is more important than the number of sources. For instance, if the luminance of a number of sources is halved, the reduction in glare is greater than is achieved by reducing the number of such sources by half. Indeed, the latter procedure has little effect on discomfort glare.

The remaining two factors are less self-evident. Glare decreases rapidly as the brightness source is moved away from the direct line of vision; thus, the glare produced depends on the source's position in the field of view. The amount of discomfort glare produced by a source is inversely proportional to the background luminance (eye adaptation level). Thus, a ceiling fixture with a luminance of 4000 cd/m^2 at 65° might easily constitute a source of discomfort glare in a space with an eye adaptation level of 150 cd/m^2. The same fixture would not be objectionable in a daylight condition, where the eye adaptation level might be 1500 cd/m^2. A more striking example is that of an automobile's headlights, which at night are so severe a source of glare as to constitute disabling or blinding glare, whereas in daylight, with its concomitant high eye adaptation level, headlights, although very noticeable, are not usually disturbing.

Keeping in mind the dependence of direct glare on eye adaptation level, a useful design recommendation is that the luminance of large sources should not exceed 2500 cd/m^2 and that of small sources should not exceed 7500 cd/m^2. The former is roughly the luminance of blue sky; the latter approximates that of a fluorescent lamp. The terms "large" and "small" depend not only on the actual physical dimensions of the source but also on the distance from the observer. That is, the actual criterion is apprehended size, or subtended visual angle, as shown in Fig. 13.20.

The glare effect of a number of individual direct glare source contributions in an interior space can be quantified by the criterion called *visual comfort probability* (VCP), which is defined as the percentage of normal-vision observers who will be comfortable in that specific visual environment. IESNA has established a set of standard conditions for which VCP of sources can be calculated. These include a 1000-lux illuminance, representative room dimensions, fixture height and observer position, and a head-up field of view limited to 53° above and directly forward from the observer (Fig. 13.24).

Direct glare will not be a problem if all three of the following conditions are satisfied:

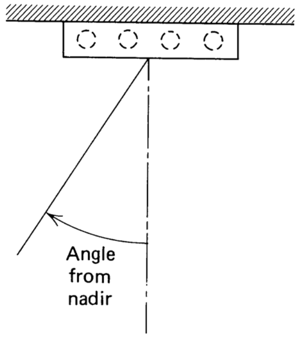
1. The VCP is 70 or more.
2. The ratio of maximum-to-average luminaire luminance does not exceed 5:1 (preferably 3:1) at 45°, 55°, 65°, 75°, and 85° from the nadir, crosswise, and lengthwise.
3. Maximum luminaire luminances crosswise and lengthwise do not exceed the following:

Angle Above Nadir (degrees)	Maximum Luminance (cd/m^2)
45	7710
55	5500
65	3860
75	2570
85	1695

4–40-W Lamps
Prismatic Lens Diffuser

Average Luminance Data cd/m²

Vertical Angles	Across Axes	Along Axes
60°	2000	1750
65°	1060	1075
70°	500	560
75°	410	380
80°	480	343
85°	560	420



Reflectances:
Wall 50%
Ceiling cavity 80%
Floor cavity 20%
Work plane illumination: 1000 lux

IES Visual Comfort Probability Data

Room Size W (ft)	L (ft)	Luminaires Lengthwise 8.5	10.0	13.0	Luminaires Crosswise 8.5	10.0	13.0
20 ×	20	80	77	76	79	75	72
	30	80	78	76	79	76	73
	40	82	79	77	79	77	74
	60	80	80	78	79	77	75
30 ×	20	84	80	77	82	78	74
	30	83	80	77	81	79	74
	40	82	80	78	81	79	75
	60	82	80	78	80	79	75
	80	82	80	78	80	78	76

(Ceiling Height (in ft))

Fig. 13.25 *A typical set of manufacturer's published VCP and luminance data.*

A typical set of manufacturer's luminance and VCP data is shown in Fig. 13.25 for a ceiling-mounted fluorescent fixture with four 40WT12 lamps. Note that all VCP values are considerably above the minimum criterion of 70. If full VCP data of this type are not available, they can be calculated with almost any lighting calculation program, given the luminaire luminance data. Despite the usefulness of the VCP criterion, it is inherently limited by its own standard conditions, which are not easily applied to other situations:

1. In small spaces, VCP has little significance.
2. Tabulated VCP figures are given for the *worst* viewing position in the room. Because VCP varies dramatically with observer position, the VCP values given are always lower than the space's *average* VCP.

In view of these (and other) reservations, most of which tend to make the actual direct glare situation better than the VCP calculation would indicate, it is recommended that layouts giving a VCP of somewhat below 70 ought not be discarded out of hand. Instead, they should be examined carefully and, if possible, several observer positions calculated using one of the many readily available computer analysis programs. With these as a guide, the designer can usually rearrange and substitute equipment to obtain the desired condition.

See Section 16.4 for a comparison of the direct glare characteristics of lighting fixture diffusers.

13.18 VEILING REFLECTIONS AND REFLECTED GLARE

Although there is no generally accepted convention with respect to nomenclature, many people refer to *reflected glare* when dealing with specular (polished or mirror) surfaces, and to *veiling reflections* when considering source reflections in dull or semi-matte finish surfaces (which always exhibit some degree of specularity). This discussion uses the terms interchangeably.

(a) Nature of the Problem

The problem of veiling reflections is much more complex than that of direct glare because it involves both the source *and* the task, and is inherent in the act of seeing (Fig. 13.26). Vision is produced by light being reflected from the object seen (unless the object itself is emitting light, e.g., a light bulb, the sun, a screen, computer screen, etc.). Thus, if a mirror replaced the object being viewed, we would see the source(s) of light clearly (Fig. 13.26*a*).

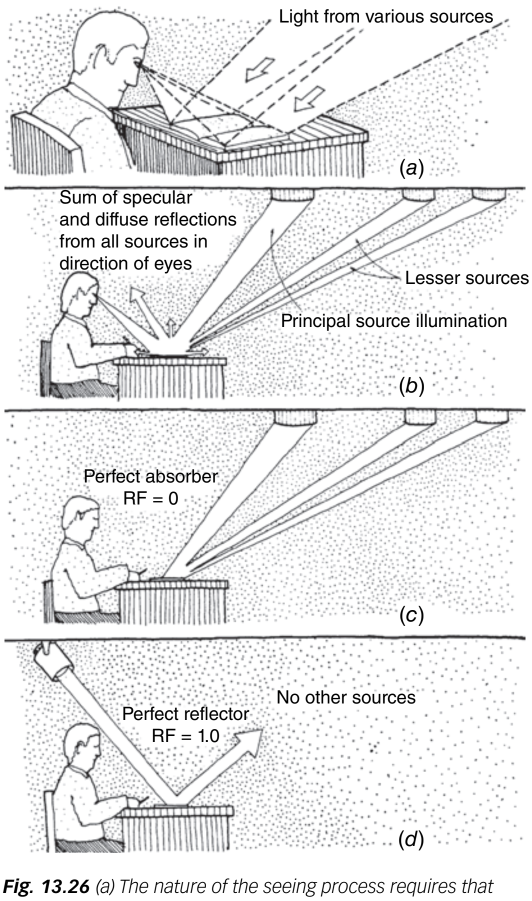


Fig. 13.26 *(a) The nature of the seeing process requires that light from the source(s) be reflected by the task into the eye. (b) The light entering the eye is the sum of all of the reflected light, specular and diffuse, from all sources in the direction of the eye. If the task is specular, all of the sources will be seen reflected in the task. (c) A perfectly absorptive object is jet black because it reflects nothing. (d) A perfectly reflective object positioned as shown is also black because geometrically it cannot reflect light into the eyes.*

In commercial spaces there are usually one or more lighting fixtures near the observer that furnish most of the light by which to see. These *principal* sources are the main contributors to reflected glare. Other, more remote fixtures in the room are lesser sources of veiling reflections (Fig. 13.26*b*).

To the extent that the sources can be seen in the vision task, glare exists. It is imperative in understanding this problem to appreciate the importance of the reflection characteristic of the object being viewed. If the object were perfectly absorbent—that is, if it had a reflection coefficient of 0%—it would appear completely black, as no light would be reflected into the eye (Fig. 13.26*c*). Conversely, if the object were perfectly specular, like a clean mirror, and no light source were within the geometry of reflection, it too would appear black (Fig. 13.26*d*). Thus, if we took a clean mirror out on a moonless night and shined a light on it from over our shoulder, it would be practically invisible because no light would be reflected back into our eyes.

The reader might try this experiment: In an inside space with a single overhead luminaire, try to examine the surface of a very clean, dust-free mirror. You will find that the best angle to hold it is *almost* at the angle at which the light source is seen. This is because the mirror is *almost* completely specular, and it is the slight diffuse reflection near the viewing angle that permits us to see the surface. This means that reflected glare is due to task surface specularity, whereas object definition (that is, the ability to see the task itself) is due to task surface diffuseness. A corollary of this conclusion is that veiling reflections, which are caused by mirroring of a source in the task, are proportional to source luminance and substantially independent of illuminance level—the brighter the source, the more troublesome its reflection.

Glare sources within the geometry of reflected vision are shown in Fig. 13.27, and the effects are shown in Fig. 13.28. Figure 13.27 clearly shows that although large sources are difficult to avoid, small sources can usually be easily avoided by a small change in the source-task-eye geometry (for instance, by moving the head or tilting the task). Table 13.6 lists a few sample reflectance figures to demonstrate that most materials exhibit

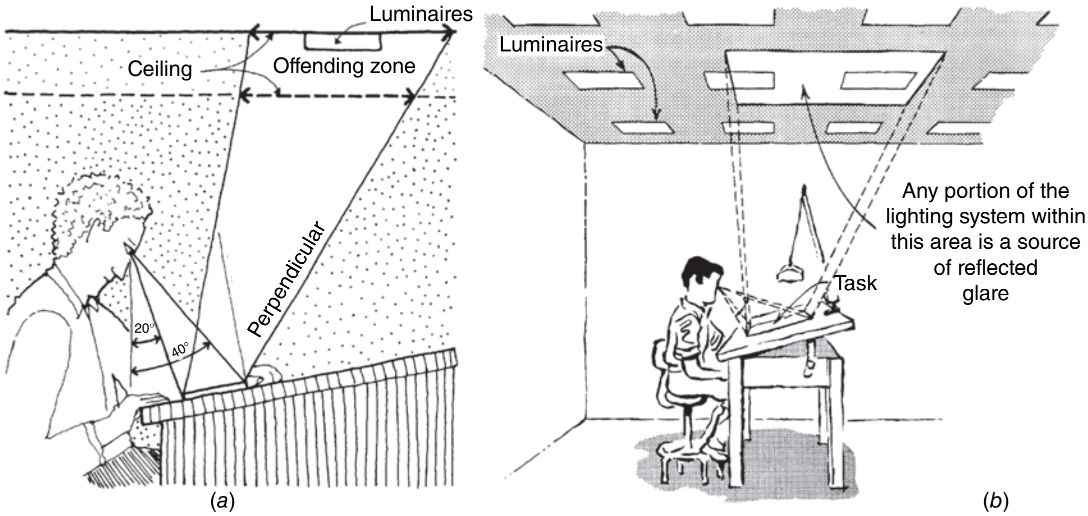


Fig. 13.27 *Geometry of reflected glare. (a) Because normal desktop, head-down viewing angles vary from 20° to 40° from the vertical, the offending zone is the area on the ceiling corresponding to specular reflection between these two angles. Note that the higher the ceiling, the larger this area becomes. (b) In an office situation, the draftsman would see ceiling fixtures in the offending zone reflected in his instruments and work. Note the important fact that the offending zone moves back and becomes smaller as the table tilts up.*

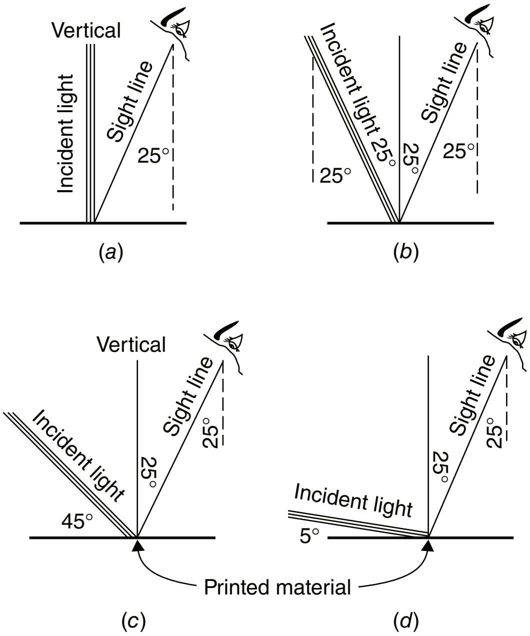


Fig. 13.28 *The usual viewing angle to a horizontal surface is between 20° and 40° from the vertical; we show 25° because it is the most common viewing angle. With vertical incident light on a diffuse surface (such as a textbook page) (a), the print can appear dark and clear. When the angle of light incidence is equal to the viewing angle (b), a mirror reflection situation can make the page illegible. Even with a diffuse-type paper, the print is light at best and almost invisible at worst. As the angle of incidence becomes larger (c), reflected glare decreases. When the incident light is at a very low angle (d), there is little reflected glare, and the print appears lighter.*

both specular and diffuse reflectance. In studying Fig. 13.27, it is important to note that a majority of visual work is done in the zone of 20° to 40° from the vertical, below the eye, with a maximum at the 25° reading angle (Fig. 13.29).

(b) Contrast Reduction

The principal effect of the reflection of a light source in a visual object is a reduction in contrast between the object and its background—and hence, a reduction in the object's visibility. It is as if a bright veil were spread over the object being viewed, which accounts for the term *veiling reflection*. As the angle of the incident light approaches the viewing angle, the specularly reflected component

TABLE 13.6 Typical Reflectances

	Reflectance	
Material	**Specular**	**Diffuse**
Matte black paper	0.0005	0.04
Matte white paper	0.0030	0.77
Newspaper	0.0065	0.68
Very glossy white photo paper	0.048	0.83
Metallic paper—copper	0.11	0.28
Dull black ink	0.006	0.045
Super gloss black ink	0.039	0.016

Source: Courtesy of IESNA.

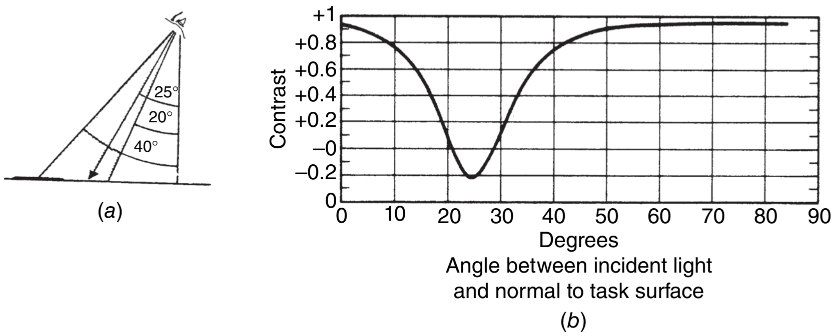


Fig. 13.29 *(a) The normal viewing angle of a task on a horizontal surface ranges from 20° to 40° from the vertical. The most common viewing angle is 25°. (b) Graph showing contrast reduction of a task with a specular background (such as a sheet of glossy paper) as a function of the angle between incident light and a line normal to the task surface. Viewing angle is assumed to be 25° from normal. Note that between 22° and 27° the contrast is negative. This indicates that background luminance exceeds that of the task, making the task essentially invisible. What is visible, clearly, is a reflected (mirrored) image of the source.*

of the light becomes more and more pronounced, and task contrast drops. This is clearly visible in Figs. 13.28 and 13.29. The worst situation occurs when the incident angle equals the viewing angle. When the specular reflectance of the task and background is high, as with the glass screen of a visual display terminal, for instance, an image of the source is superimposed on the object, making viewing impossible (Fig. 13.29). However, even with the highly specular finish of "slick" magazine paper, vision is still possible because of the very high contrast between black ink and white paper, although with much reduced clarity and considerable annoyance.

When considering specular *and* diffuse reflectance, the equation for contrast given in Section 13.12 must be rewritten as

$$C = \frac{(L_{BD} + L_{BS}) - (L_{TD} + L_{TS})}{L_{BD} + L_{BS}} \tag{13.9}$$

where L_B and L_T are background and task luminances caused by diffuse (D) and specular (S) reflectance; that is, L_{BS} is the background luminance due to its specular reflectance, and so forth. If we were to rework the calculation of contrast of Section 13.12, including specularity, the result would be much different.

EXAMPLE 13.5 Assume an interior space lighted to an average illuminance of 75 fc (750 lux) using bare bulb fluorescent fixtures (luminance = 7000 cd/m^2 [2000 fL]). The task is drawing with India ink on vellum. Reflectances are:

	Specular	Diffuse
Ink	0.021	0.038
Paper	0.018	0.71

Calculate the task contrast without and with reflection of the 2000 fL source on the work.

SOLUTION

1. Without specularity, using Equation 13.6 for diffuse reflection only:

$$C = \frac{R_B - R_T}{R_B} = \frac{0.71 - 0.038}{0.71} = 0.947$$

2. With specularity, using Equation 13.9,

$$C = \frac{(L_{BD} + L_{BS}) - (L_{TD} + L_{TS})}{L_{BD} + L_{BS}}$$

where

$$L_{BD} = 75 \text{ fc} \times 0.71 = 53.25$$
$$L_{BS} = 2000 \text{ fL} \times 0.018 = 36.0$$
$$L_{TD} = 75 \text{ fc} \times 0.038 = 2.85$$
$$L_{TS} = 2000 \text{ fL} \times 0.021 = 42.0$$

and

$$C = \frac{(53.25 + 36) - (2.85 + 42)}{53.25 + 36} = 0.497$$

which is just over half of the previous contrast! If the contrast is normalized to the maximum contrast

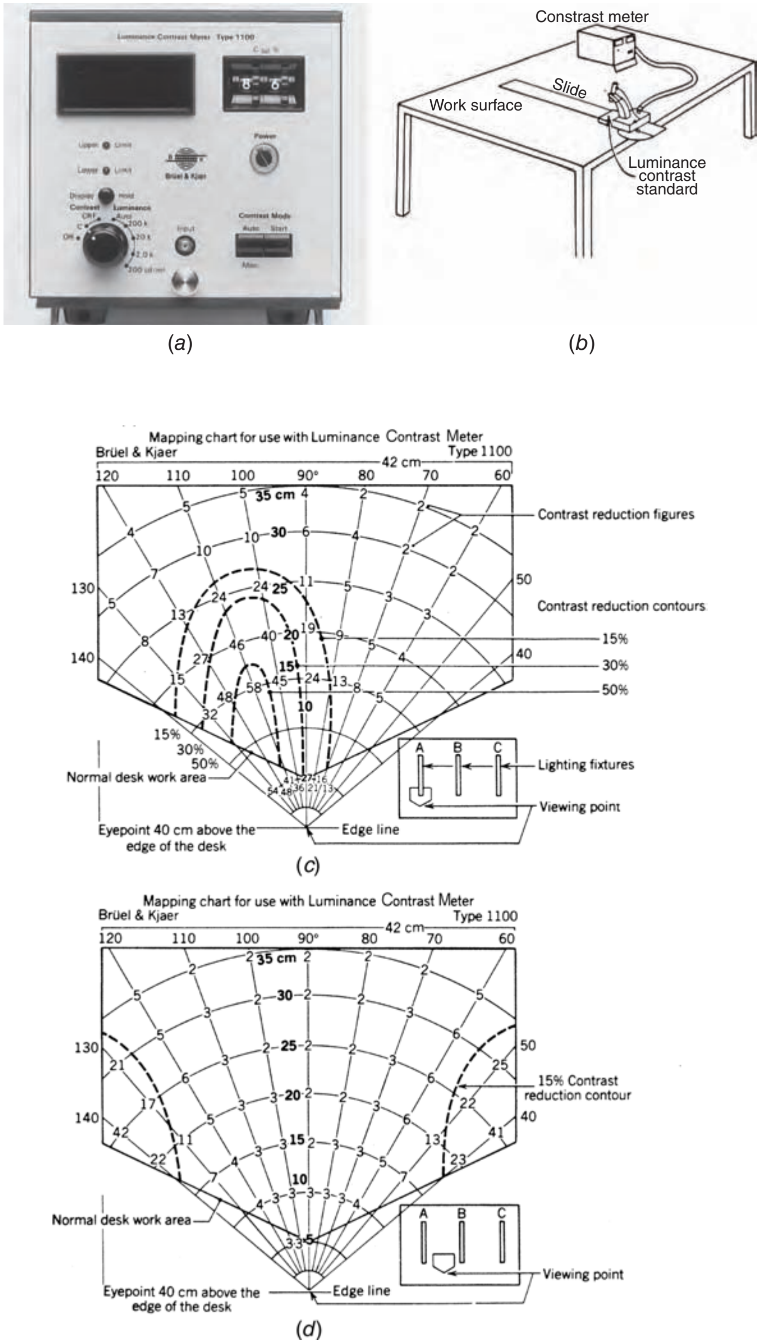


Fig. 13.30 *(a) This unit is a high-precision electronic digital instrument that measures luminance, luminance ratio, contrast, and contrast reduction. Luminance range is 0 to 200,000 cd/m*^{2} *(56,400 fL) at high accuracy. (b) The meter measures contrast reduction at a specific viewing angle. (c) Note that with a lighting fixture directly in the offending zone—that is, above and in front of the viewer—a severe loss of contrast occurs over much of the work surface. (d) By shifting the relative position of the viewer and the source so that no source exists in the offending zone, contrast reduction is held to 3% to 4% over most of the work surface. Contrast reduction in the normal work area should not exceed 15%. (Courtesy of Brüel & Kjær.)*

(as is usually done), the contrast reduction R can be expressed as

$$R = 1 - \frac{C}{C_{MAX}} \tag{13.10}$$

Thus, in this case, contrast reduction would be

$$R = 1 - \frac{0.497}{0.947} = 0.47$$

That is, the contrast reduction would be 47%. ■

A similar calculation for black, clearly typewritten material on good white bond paper yields a contrast reduction from 94% to 77%, or R = 17%. This 77% figure simply serves to emphasize the fact that with high task-to-background contrast, effective seeing is possible almost regardless of the lighting condition. However, this most emphatically does not relieve the lighting designer of the responsibility to provide a comfortable and efficient lighting environment in which pronounced veiling reflections do not exist. In general, any contrast reduction of more than 15% is undesirable.

Because both specular and diffuse reflectances frequently vary with the angle of view, and exact figures are rarely available, accurate calculations are difficult. If a lighting system exists or a mock-up can be made, measurements of contrast reduction can be made accurately with a contrast/luminance meter of the type shown in Fig. 13.30. In such an experiment, a standard contrast device that is designed to correspond to a normal office task (e.g., reading black typeface on a white paper background) is positioned on the work surface, and subsequently exposed to ambient illumination. The task contrast is then measured at the same angle at which it would normally be viewed. Contrast reduction is automatically calculated and displayed.

13.19 EQUIVALENT SPHERICAL ILLUMINATION AND RELATIVE VISUAL PERFORMANCE

(a) Equivalent Spherical Illumination

Another way of approaching the problem of contrast reduction is to define a reference lighting system that is effectively free of veiling reflections, and then relate an actual lighting system to it with a figure of merit. Conversely, one can measure the effectiveness of a given lighting system in terms of the equivalent glare-free system. Both of these ideas, which are essentially the same, are the basis of the concept of *equivalent spherical illumination* (ESI).

In order to achieve a lighting system almost free of reflected glare, it is necessary to construct an enclosed volume whose surfaces are uniform in their diffuse reflectivity and whose primary source is obscured to the maximum extent possible. As illustrated (Fig. 13.31), the integrating sphere is such a device. Light is introduced from the outside, split by a deflector, and evenly distributed throughout the sphere by the multiple reflections from the white-painted walls. The result is an evenly illuminated volume. When a task is introduced, the illumination falling on it is *entirely* uniform; that is, there are no high-luminance sources reflected in it. It is therefore termed *spherically* illuminated. (Note the parallel to overcast sky illumination.) The extent to which any other illumination system can duplicate this glare-free environment is that system's *equivalent* spherical illumination (ESI), representing the portion of its total illumination that is spherical—that is, diffuse and glare-free. ESI is determined by comparing contrast rendition in the spherical and test systems.

A study of school lighting (Fig. 13.32) gave the illustrated results for four viewing positions in a classroom lighted with ceiling-mounted continuous rows of 2-ft × 4-ft, 4-lamp, 40-W fluorescent fixtures with lens-type wraparound diffusers on 10-ft centers. It is vital to note that:

1. ESI depends entirely on the viewing position and viewing angle, other factors in the space being equal.
2. In an ostensibly well-lighted (215 fc) position (M1), the glare-free illuminance is only 28 fc! This does not mean that visual work in this position is impossible. It does mean, emphatically, that in position M1, a pronounced veiling reflection exists on all specular objects. (Because of the size, orientation, and location of the glare source, this reflected glare is difficult to avoid.) It further means that a large amount of energy is being utilized (effectively wasted) to produce essentially negative results.

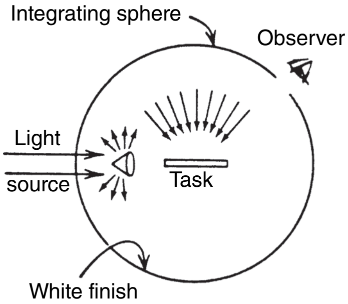


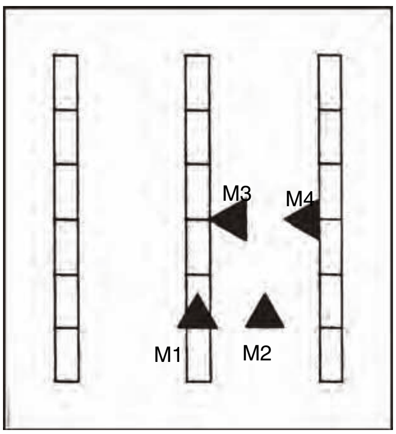
Fig. 13.31 *Spherical illumination is produced by illuminating an object by diffuse reflection from the inside walls of an integrating sphere. The light source and observer are normally external.*

The results could have been anticipated, at least qualitatively, by an examination of the observer positions vis-à-vis the layout. Positions M1 and M3 have bright sources in the offending zone—M1 more so than M3—as is borne out by the results. M2 is an excellent position in that it receives light contributions from the two sides, its illuminance value being lower than the others due to wide row spacing. M4 is ideally placed; no glare sources are in the offending zone, and a row of fixtures is positioned *behind* it, which makes it geometrically impossible for these fixtures to act as a glare source. The ESI analysis gives quantitative expression to our qualitative judgment, which makes it a valuable design tool. Note particularly that the ESI results shown in Fig. 13.32 clearly correspond to the results of a similar test made with the contrast meter, as shown in the charts of Fig. 13.30.

As with VCP criteria for direct glare, with ESI there are also ameliorating factors that generally make a given lighting system better than these criteria figures would indicate. Some of these factors have already been mentioned but bear repeating.

1. ESI is critically dependent on observer position and viewing angle. Although position is generally fixed by chair location, observers can and do change their viewing angle and head aspect to correct for glare situations.
2. The nature of the task (i.e., its specularity) is assumed to be fixed and unique. In some situations the task nature varies, and thus also the contrast. When tasks are constant, severe veiling reflections frequently lead to measures being taken that improve the task, the lighting, or both.
3. The lighting distribution characteristic of the fixture involved is a critical factor in glare production. The characteristic of a wraparound lens diffuser is such that considerable light falls in the glare zone. Other diffuser characteristics yield different results.

The concept and use of ESI have come under considerable criticism in the professional lighting literature because: ESI addresses contrast, which is not



		Observer Position			
		*M*1	*M*2	*M*3	*M*4
TI	2L	108	92	125	118
	4L	215	185	250	235
CRF	2L	0.75	1.00	0.82	1.01
	4L	0.76	1.00	0.83	1.03
ESI	2L	17.8	91.9	31.5	127.8
	4L	28.4	185.3	58.1	308.3

TI–Task illuminance
2L–2 lamps (inside pair)
4L–4 lamps
CRF–Contrast Rendition Factors

Fig. 13.32 *A test classroom illuminated by three widely spaced rows of four-lamp fixtures with lens-type wraparound diffusers. Observer positions are shown by arrows. The row of fixtures in front of position M4 is too far forward to be in the offending zone. (From Sampson, 1970.)*

identical with visibility; it requires recalculation for even the small geometry changes that can change contrast dramatically; it tracks raw footcandles; and it is based on extrapolation from threshold conditions, the efficacy of which has been called into doubt. These published reservations and criticisms of ESI have disturbed the lighting profession sufficiently to result in a wide abandonment of its use.

The ESI procedure, however, does exactly what it is designed to do: to point out locations of poor lighting geometry immediately and quantitatively, and to flag luminaires with unsuitable distribution characteristics for the proposed use. That is, as stated in the 1981 *IES Lighting Handbook*, it is "used as a tool in determining the effectiveness of controlling veiling reflections and as part of the evaluation of lighting systems."

(b) Relative Visual Performance

In more recent years, a metric called *relative visual performance* (RVP) has appeared in the literature and has gained considerable acceptance. It tests (also via computer calculation) the effectiveness (i.e., the relative [to perfection] visual performance of a given visual environment) of task accomplishment, in regard to speed and accuracy. Like ESI, it is based on luminance and contrast, but unlike ESI, it judges the relative performance of a task rather than simply contrast reduction. It seems to ignore the discomfort of veiling reflections if the task can be performed efficiently. The RVP for a number of common lighting layouts with various types of lighting fixtures reveal uniformly high values varying between 0.95 and 0.99, which makes effective judgment of glare situations very difficult. Designers are encouraged to use the available lighting programs to calculate ESI and RVP for proposed lighting layouts and, where possible, to compare the results to the post-construction performance of the system.

13.20 CONTROL OF REFLECTED GLARE

Because the causes of veiling reflections are well understood, it would seem that a solution to the problem should have long since been developed. Unfortunately, this is not the case. Although there is no known lighting method or material that completely eliminates veiling reflections, there are a number of techniques that minimize contrast loss due to veiling reflections while maintaining adequate illumination. These are:

- Physical arrangement of sources, task, and observer so that reflected glare is minimized (see Section 13.20*a*).
- Adjusting brightness (eye adaptation level) so that objectionable brightness is minimized (see Section 13.20*b*).
- Design of the light source so that it causes minimal reflected glare (see Section 13.20*c*).
- Changing the task quality (see Section 13.20*d*).

(a) Physical Arrangement of System Elements

The task of arranging the lighting geometry to avoid sources of high luminance at reflection angles when dealing with specular tasks can be a challenge. This is often difficult to accomplish in modern offices, which frequently have both horizontal and vertical work surfaces, the vertical being the specular screen surface of digital displays. The latter problem is so widespread that it can pervade the design of office lighting. As should be clear from Figs. 13.30 and 13.32 and the related discussion, in a space using multiple sources, particularly in continuous rows, placing the work between rows with the line of sight parallel to the long axis of the units is an effective technique (see Fig. 13.32, position M2). Position M4 is dangerous in that the center row can be a source of reflections. In this case it is not, due to the 10-ft row spacing. Note that the offending zone for horizontal tasks depends on the tilt of the desk. Thus, for a horizontal desk, the offending zone is forward of the desk, as in Fig. 13.33*a*; with an elevated table, the ceiling glare source zone may well be behind the source, as in Fig. 13.33*b*.

All of the geometric solutions mentioned presuppose a detailed, fixed furniture layout, a situation that pertains to many but certainly not all cases. In the absence of such data, two alternatives are possible: a uniform layout with furniture adjusted to it, or vice versa. In reality, a combination of both is the most practical approach. Because low watts per square foot budgets have made ducted lighting fixture heat removal systems (air troffers) much less prevalent, fixtures are

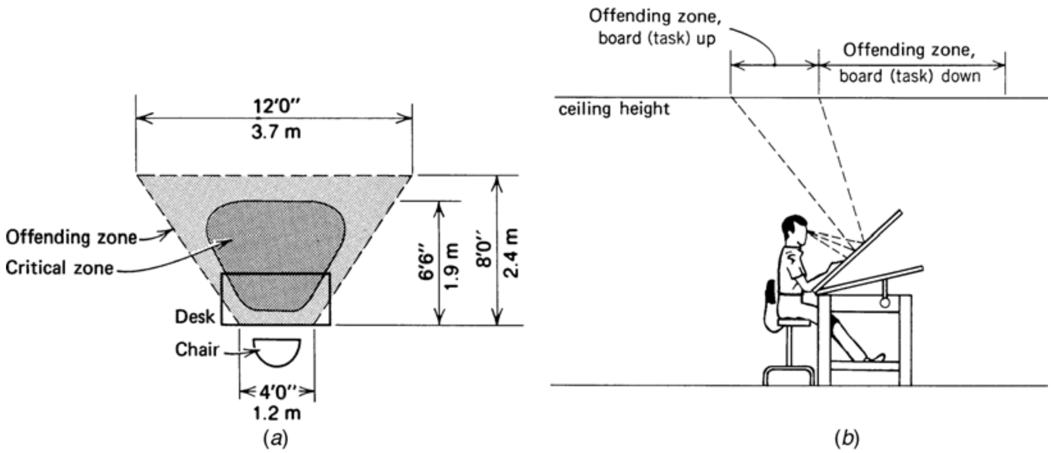


Fig. 13.33 *(a) If luminaires are kept out of the trapezoidal offending zone, contrast will be excellent. If the bulk of one or more luminaires projects into this zone, and in particular into the critical zone, contrast will drop sharply. The dimensions shown are for a flat desk 3 ft × 5 ft (0.91 m × 1.5 m) and a 9-ft (2.7-m) ceiling height. (b) The dependence of the glare zone on table tilt is illustrated. The offending zone becomes smaller as the table is raised, so that with a table near the vertical position, glare is all but eliminated. (a) from Ross and Baruzzini, Inc., 1975.*

easily shifted. This mobility is further enhanced by the extreme flexibility of lighting fixtures fed from ceiling plug-in raceways. Figure 13.34 shows such a rearrangement, which results in saving five fixtures, a load reduction of 800 W, and an *improvement* in visibility.

(b) Control of Area Brightness and Eye Adaptation Level

As discussed in Section 13.12, loss of contrast can be compensated for (and glare reduced) by increasing overall non-glare illumination. In so doing, we are simply making the task brighter in order to override the detrimental veiling reflection. The problem with this technique, however, is that a large increase in illuminance is required to overcome the glare. This increase can, in many instances, be most practically accomplished not by increasing overall room illumination—which comes with extremely high energy consumption—but by adding a supplementary task-lighting source so arranged as to be free of reflected glare. By making this supplementary source's position adjustable (as in Fig. 13.27*b*), we accomplish three things:

1. Veiling reflections are overcome.
2. The high level of illumination needed for exacting tasks is provided with minimum energy expenditure.
3. The observer is granted complete control, with resultant optimum lamp placement, as well as psychological satisfaction that generally prevents worker complaint. (The optimum position is generally to the left and slightly forward of the task.)

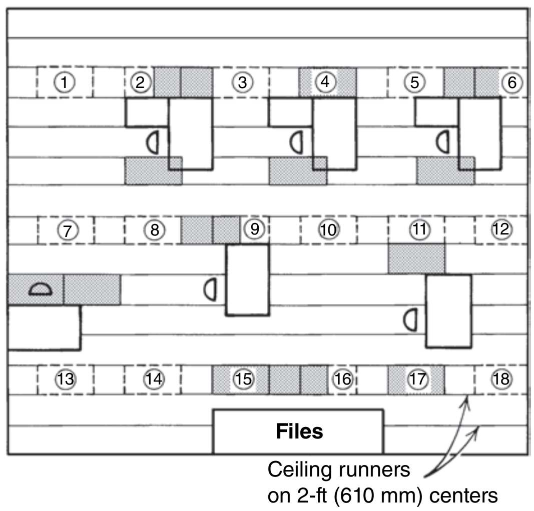


Fig. 13.34 *The original uniform fixture layout utilized three rows of six 2 ft × 4 ft (0.6 m × 1.2 m), four-lamp fixtures, giving a total load of 2880 W, a load density of 2.6 W/ft^2 (28 W/m^2), and a uniform illuminance level of approximately 90 (raw) fc (900 lux). The original layout is shown dotted and numbered. The rearranged layout uses 13 fixtures (shown shaded) for a total of 2080 W, a load density of 1.9 W/ft^2 (20.5 W/m^2), and more than 100 ESI fc (1000 lux) on each work surface. In addition, five fixtures are saved. Note: This level of illuminance is justified only for difficult visual tasks.*

We can demonstrate the effectiveness of a supplemental desk lamp by returning to the situation described in Example 13.5.

EXAMPLE 13.6 Recalculate the contrast reduction of the ink-on-vellum visual task of Example 13.5, assuming that a desk lamp raises the illuminance to 200 fc (2000 lux) and is positioned so as to be glare-free. (Note: An adjustable lamp with 2 at 15-W fluorescent tubes produces approximately that luminance on the desk.)

SOLUTION

Contrast from Equation 13.9:

$$C = \frac{(L_{BD} + L_{BS}) - (L_{TD} + L_{TS})}{L_{BD} + L_{BS}}$$

where

$$L_{BD} = 200 \text{ fc} \times 0.71 = 142$$

$$L_{BS} = 2000 \text{ fL} \times 0.018 = 36$$

$$L_{TD} = 200 \text{ fc} \times 0.038 = 7.6$$

$$L_{TS} = 2000 \text{ fL} \times 0.021 = 42$$

and

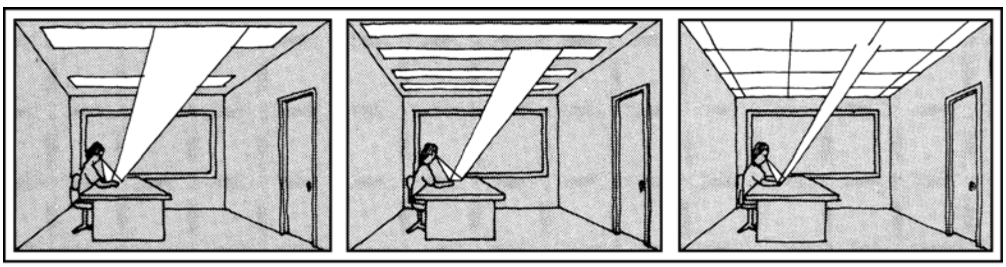
$$C = \frac{(142+36)-(7.6+42)}{142+36} = 0.72$$

With this contrast (0.72), the contrast reduction from the original no-glare situation has been improved from the original 47% reduction (0.947 to 0.497) to 24% reduction (0.947 to 0.72). However, because even a contrast reduction of 24% is undesirable, a change in task-source geometry or a change in source luminance would be required, assuming that the task itself must remain unchanged. ■

(c) Control of Source Characteristics

The reflected luminance that causes loss of contrast is proportional to the luminaire's luminance at that viewing angle, and therefore may be reduced by reducing luminaire luminance at that angle. This can be accomplished in four ways:

1. *Dimming or switching lamps.* Reducing the total output of a fixture also reduces its output in the critical portion of the ceiling glare zone and can actually *increase* the ESI illuminance (i.e., improve task contrast).
2. *Using luminaires with lower overall luminance.* In lieu of using a few small high-output sources, utilize larger-area, low-output sources (Fig. 13.35). This has the effect of reducing the source luminance in the ceiling glare zone, while increasing the illumination contribution from outside the glare zone—resulting in better contrast for the same or lower illuminance level (lux). The disadvantage of this technique is an increased lighting fixture cost.
3. *Using the luminaire as a primary source to illuminate a large, low-brightness secondary source.* To overcome the economic disadvantage of multiple low-output, low-luminance sources, the ceiling can be used as a secondary source illuminated from high-output indirect or semi-indirect fixtures. These sources, which can be fluorescent or HID (e.g., metal–halide), have the advantage of high efficiency. The space's ceiling height must be sufficient to permit suspending the unit while avoiding "hot spots" on the ceiling. The minimum suspension length depends on the luminaire characteristics and is normally provided by the manufacturer.



(*a*) (*b*) (*c*)

Fig. 13.35 A concentration of light in the glare zone (a) produces the largest amount of reflected glare. As the number of light sources is increased (b) in the glare zone, and luminance is decreased, reflected glare is decreased. The least glare is from an all-luminous ceiling, which also has the lowest luminance (c).

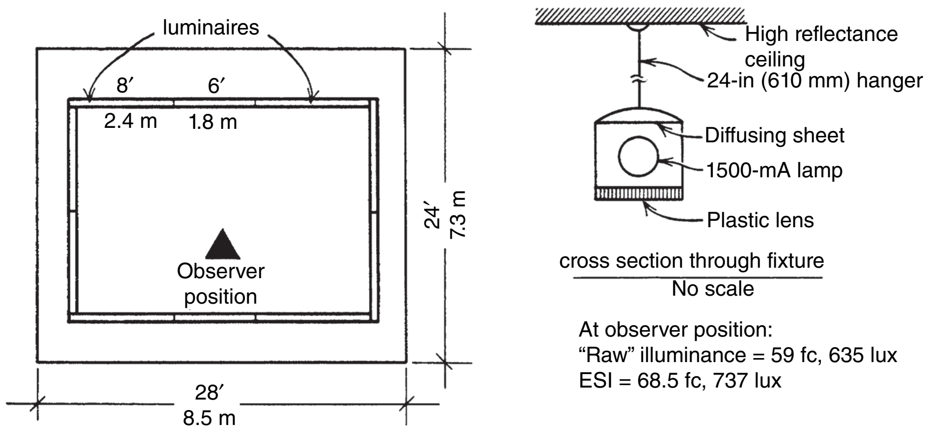


Fig. 13.36 *With a high-reflectance diffuse finish ceiling, this semi-direct perimeter lighting installation yields a higher ESI illuminance than raw illuminance at the viewing location illustrated, indicating excellent contrast rendering. The plastic lens at the bottom of the fixture serves to provide perceived light source luminance and to avoid an impression of gloominess, despite the satisfactory overall luminance level. (From Sampson, 1970.)*

To ensure high efficiency, the ceiling should be painted with a high-reflectivity matte white paint and kept clean. Results obtained from a semi-indirect installation using 1500-mA, very-high-output lamps are shown in Fig. 13.36.

4. *Reduce the luminaire luminance only at the offending angles*. Because most horizontal task vision takes place between 20° and 40° from the vertical (see Figs. 13.27 and 13.30), any fixture that emits little or no light below 40° from the horizontal *cannot* produce a veiling reflection, regardless of its position in the field of view (Fig. 13.37). As a result, diffuser manufacturers produce prismatic diffusers the output of which is diminished below 30° and above 60° in order to minimize both reflected and direct glare. Due to the characteristic shape of the distribution curve, they are known industry-wide as *batwing* diffusers. For observers positioned so that their sight lines are parallel to the longitudinal axis of the ceiling fixtures, lenses with linear (side-to-side) batwing characteristics perform well. If the observing position varies in aspect with respect to the fixture, a radial batwing curve (in all directions) is required. Note carefully that these diffusers have only limited usefulness in reducing reflected glare in specular vertical surfaces (digital display screens). All types of diffusers and their characteristics are discussed in Section 16.4.

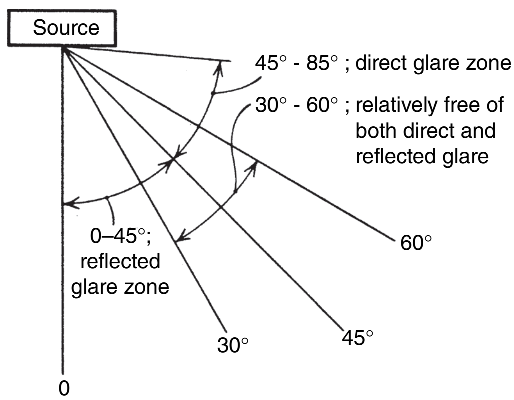


Fig. 13.37 *Glare zones are 0° to 45° and 45° to 85° for reflected and direct glare, respectively. Therefore, a diffuser that emphasizes the 30° to 60° zone will be least objectionable on both counts.*

(d) Changing the Task Quality

At this point, it should be clear that reducing the task specularity is at least as effective a means of reducing veiling reflections as changing the lighting system characteristics—if not more so. It is therefore recommended that task contrast and specularity be actively considered and recommendations made in a framework of energy and cost effectiveness. Thus, to produce adequate visibility it is often cheaper, and always more economical in terms of energy use, to upgrade the task (in the visibility sense) than to change the lighting system.

13.21 LUMINANCE RATIOS

As explained previously, other factors being equal, visual performance increases with contrast—that is, with the difference in luminance between the object being viewed and its immediate surroundings. Conversely, however, the difference between the average luminance of the visual field (task) and the remainder of the field of vision should be low, to avoid the discomfort of large, rapid changes in eye adaptation level. Restated, *contrast is desirable in the object of view but undesirable in the wider surrounding field of view*.

Providing reflectances of 50%, 30%, and 80% for walls, floors, and ceilings, respectively, and 35% for furniture, establishes a fairly high eye adaptation level so that direct glare (which results from excessive luminances in the field of view) is minimized. Recommendations for maximum luminance ratios needed in order to achieve a *comfortable* environment are presented in Table 13.7. Effective visual performance is entirely possible in environments with much higher ratios—it is simply not as visually comfortable and may be fatiguing.

To achieve the recommended luminance ratios, it is necessary to carefully control the reflectances of the major surfaces in a room. The reflectance figures given are averages for commercial and educational spaces. The marked difference between a background with proper reflectance and one with excessive brightness ratios caused by low surrounding reflectances is shown in Fig. 13.38.

TABLE 13.7 Recommended Maximum Luminance Ratios[a]

Note: To achieve a comfortable brightness balance, it is desirable to limit luminance ratios between areas *of appreciable size* as seen from normal viewing positions as follows:	
1 to one-third	Between task and adjacent surroundings
1 to one-tenth	Between task and more remote darker surfaces
1 to 10	Between task and more remote lighter surfaces
20 to 1	Between luminaires (or fenestration) and surfaces adjacent to them
40 to 1	Anywhere within the normal field of view

[a]These ratios are recommended as maximums; reductions are generally beneficial.

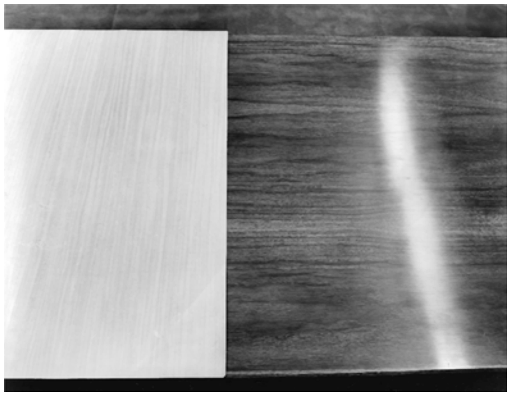


Fig. 13.38 *The reflected glare from luminaires disappears when a piece of light, diffuse linoleum is placed over the dark, polished desktop. Light-colored desktops with 35% to 50% reflectance result in task-to-background ratios within the 3:1 recommended range. Before the linoleum was placed, a reflection similar to the one seen on the right also existed on the left of the desk due to another luminaire. (Courtesy of IESNA.)*

13.22 PATTERNS OF LUMINANCE: SUBJECTIVE REACTIONS TO LIGHTING

In the list of characteristics in Section 13.12, we included *patterns of luminance* among the secondary factors in illumination—that is, the patterns of light and shadow in a space resulting from illumination. Thus, a single source may produce sharp shadows, whereas a luminous ceiling or a completely indirect illumination system may produce almost completely diffuse light. *Diffusion* is the degree to which light is shadowless—it is therefore a function of the number of directions from which light impinges on a particular point and their relative intensities.

Perfect diffusion, rarely obtainable (or desirable), would have equal intensities of light impinging from all directions—therefore yielding no shadows. The only naturally occurring example of perfectly diffuse lighting is a daytime fog, which we know to be extremely disturbing to the eye, demonstrating that some directivity is desirable. Diffusion can be judged by the depth and sharpness of shadows. A room with well-diffused illumination, resulting from multiple sources and high room-surface reflectances, yields soft multiple shadows that do not obscure visual tasks. Because purely diffuse lighting is monotonous and not entirely conducive

Fig. 13.39 *Totally diffuse lighting (a) destroys texture, whereas a combination of diffuse and directional lighting (b) produces the required modeling shadows. (Courtesy of Holophane.)*

to extended periods of work effectiveness, some directional lighting is often introduced as a complement to diffuse general lighting—thus producing a more stimulating environment via variations in shadows and brightness. Where texture must be examined or surface imperfections detected by grazing angle reflections, highly directional lighting is required. Indeed, as seen in Fig. 13.39, directional light is what creates shape and is precisely the characteristic best used to influence architectural space and form.

Sections 15.10 through 15.15, which deal with systems of lighting, illustrate a few of the light/dark patterns produced by different lighting arrangements. There are various combinations of uplighting and downlighting that can be implemented, each producing its own shadows and modeling, and each having a unique quality. It is very much in the interest of the lighting designer to be familiar with these effects so that he or she can mentally visualize them as the design progresses. Indeed, it would be well for a designer to prepare a reference sketchbook of such shadow diagrams. It is these patterns of light and darkness that produce the overall ambience, as well as the subjective perceptions and observations of sociability/isolation, clarity/fuzziness, spaciousness/crampedness, simplicity/clutter, formality/informality, boredom/excitement, definition/shapelessness, and so on. In fact, many lighting designers *begin* a lighting design by sketching the area to be lighted, showing the patterns of brightness and shadow desired to achieve their objective. This technique is most useful in non-office areas such as lobbies, waiting areas, various recreational spaces, restaurants, merchandising spaces, and so on. In office areas the technique can also be applied to provide the points of visual interest referred to in our discussion.

Color has a great deal to do with subjective reactions and is discussed separately. The subject of psychological reactions to the lighting environment is extensive and complex, and can be mentioned here only to the extent of touching on a few of the salient lighting techniques and the usual subjective responses to them.

In addition to using modeling and texture accents, points of interest and visual excitement can be created by taking advantage of small, high-brightness sources (usually called *sparkle*). Lighting installations generally yield a sense of vividness or activity proportional to the level of illumination. This is not the case with very diffusely lighted areas, which, even at high illuminance levels, are tedious. This is particularly noticeable in large, luminous ceiling installations that are especially oppressive when the ceiling is low. Small, exposed incandescent lamps, a brightly lighted, rough-textured wall, and pendant fixtures with pierced reflectors are some of the techniques that can be used to create visual interest.

Areas or points of high brightness can be used to draw visual attention. This well-known fact is used constantly in displaying merchandise. Note the following usual reactions:

- A 3:1 luminance ratio between object and surround will be noticed, but usually will not affect behavior or draw attention.
- A 10:1 luminance ratio will attract attention and, if the object is interesting, hold it.
- A 50:1 luminance ratio or higher will highlight the object thus illuminated, practically to the exclusion of all else in the field of view.

Because areas of high luminance draw the eye's attention, all of the individual brightness sources in the field of view produce an overall impression. If there is some form, order, or pattern to them (as with a pattern of lighting fixtures), then the overall impression is not disturbing—it can be thought of as visually harmonious. If, however, they are in disarray, they produce discordance in the eye precisely as noise produces discordance in the ear. This visual "noise" is frequently referred to as *visual clutter* and can be very disturbing. The designer is well advised to keep this important fact in mind when arranging light sources that are the primary sources of luminance in an enclosed space.

Other subjective reactions to lighting on which there is wide consensus are:

1. Bright walls (about 25% of the horizontal light level) increase the impression of spaciousness. Conversely, dark walls diminish a space. As a corollary, high fixture luminance attracts the eye away from the walls and diminishes spaciousness.
2. Adjustable task lights increase the feeling of control and therefore comfort.
3. Downlights (and color highlights) increase feelings of relaxation and comfort.
4. Hidden-source indirect lighting and very-low-brightness lighting fixtures cause discomfort due to the viewer's inability to locate the source of light.

FUNDAMENTALS OF COLOR

The subject of color is vast. Here we consider only a few aspects of color that are imperative for the lighting designer to understand. Furthermore, because it is difficult to discuss color without actually using it, the coverage is brief.

13.23 COLOR TEMPERATURE

A light source is often designated with a *color temperature*—for example, 3400 K for halogen lamps, 4200 K for certain fluorescent tubes, and so on. This nomenclature is derived from the fact that when a light-absorbing body (called a *blackbody*) is heated, it first glows deep red, then cherry red, then orange, until it finally becomes blue–white hot. The color of the light radiated is thus related to its temperature. Therefore, by developing a blackbody color temperature scale, we can compare the color of a light source to this scale and assign to it a *color temperature*—that is, the temperature to which a blackbody must be heated to radiate a light similar in color to the color of the source in question. Temperature is measured in Kelvin, which is a scale that has its zero point at −459.67°F. Figure 13.40 shows the assigned color temperature of some common light sources.

Strictly speaking, a color temperature can be assigned only to a light source that produces light by heating, such as the incandescent lamp. Other sources, such as fluorescent lamps, produce light by processes that are detailed in Chapter 14. Such sources are assigned a *correlated color temperature* (CCT), which is the temperature of a blackbody whose chromaticity most nearly matches that of the light source. For such sources there is *no relation whatsoever* between the operating temperature and the color of light produced.

Any nonspectral color illuminant is composed of two or more component color illuminants. When such a composite light—for example, white—falls on a surface other than black or white, selective absorption occurs. The component colors are absorbed in different proportions so that the light reflected or transmitted is composed of a new combination of the same colors that first impinged

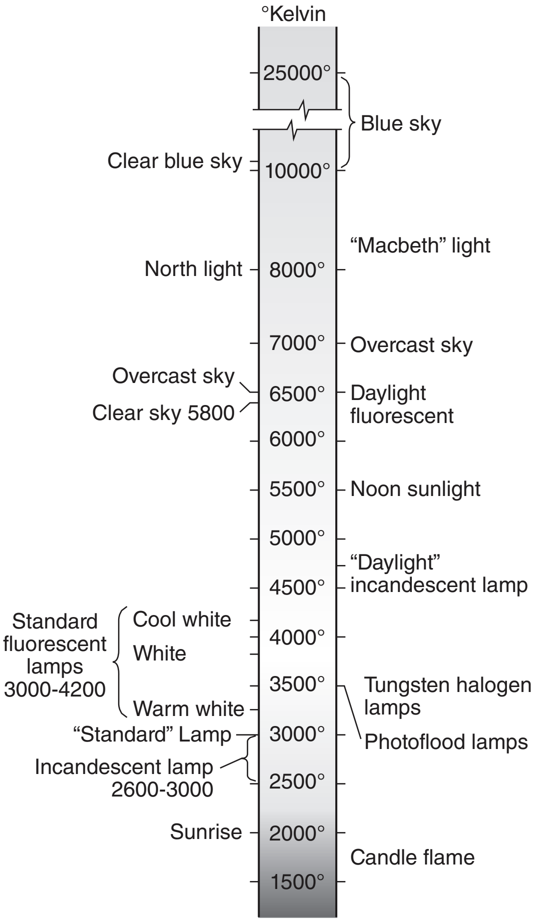


Fig. 13.40 *Approximate color temperatures of common illuminants.*

on the surface. Thus, a white light reflected from a red wall acquires a red tint because the component colors of the white light other than red were absorbed in greater proportion than the red. When reflected, the red light takes prominence, thus giving the reflected light a red tint. This is illustrated in Fig. 13.41*a*. Similarly, a white light passed through a piece of red glass emerges as a reddish light because the other components are absorbed in much greater proportions than the red. This well-known phenomenon is illustrated in Fig. 13.41*b*.

It is this phenomenon that allows us to see color; an individual object's pigmentation, by absorbing other colors of light, reflects or transmits to the eye its own hue in a greater concentration than existed in the incident light.

13.24 OBJECT COLOR

The color of the illuminant (light) and, correspondingly, the coloration of the objects within a space, constitute an important facet of the lighting quality. The two factors, however, must not be considered separately, since by definition the color of an object *is* its ability to modify the color of light incident on it by selective absorption—the color reflected or transmitted by the object is apprehended by the eye *as* the color of the object. An object, therefore, is technically said to be "colorless" (not transparent) when it does not exhibit selective absorption—that is, when an object reflects and absorbs the various components of incident light nonselectively. Thus, white, black, and all shades of gray are colorless, neutral, achromatic—or more precisely, lacking in hue.

Hue is defined as that attribute by which we recognize and therefore describe colors as red, yellow, green, blue, and so on. Just as it is possible to form a gradient from white to black with the intermediate grays, it is possible to do the same with a hue.

The difference between the resultant colors of the same hue, when arranged in this manner, is called *brilliance* or *value*. White is the most brilliant of the neutral colors, and black the least; pink is a more brilliant red hue than ruby; and golden yellow is a more brilliant (lighter) yellow hue than raw umber.

Colors of the same hue and brilliance may still differ from each other in *saturation*, which is an indication of the vividness of the hue, or the difference of the color from gray. Thus, pure gray (black plus white) has no hue; as we add color, we change the saturation without changing the brilliance. The three characteristics, then, that define a particular coloration are: *hue*, *brilliance*, and *saturation*. Using these terms, we may define "bay" as a color red–yellow in hue, of low brilliance and low saturation, whereas "carmine" can be defined as a color red in hue, of low brilliance and very high saturation.

Various systems of color classification have been devised, including the ISCC-NBS (Inter-Society Color Council and National Bureau of Standards) color system, the Munsell Color System, the Ostwald Color System, and the CIE Chromaticity Diagram. In the well-known and widely used Munsell Color System (Fig. 13.42), brilliance is referred

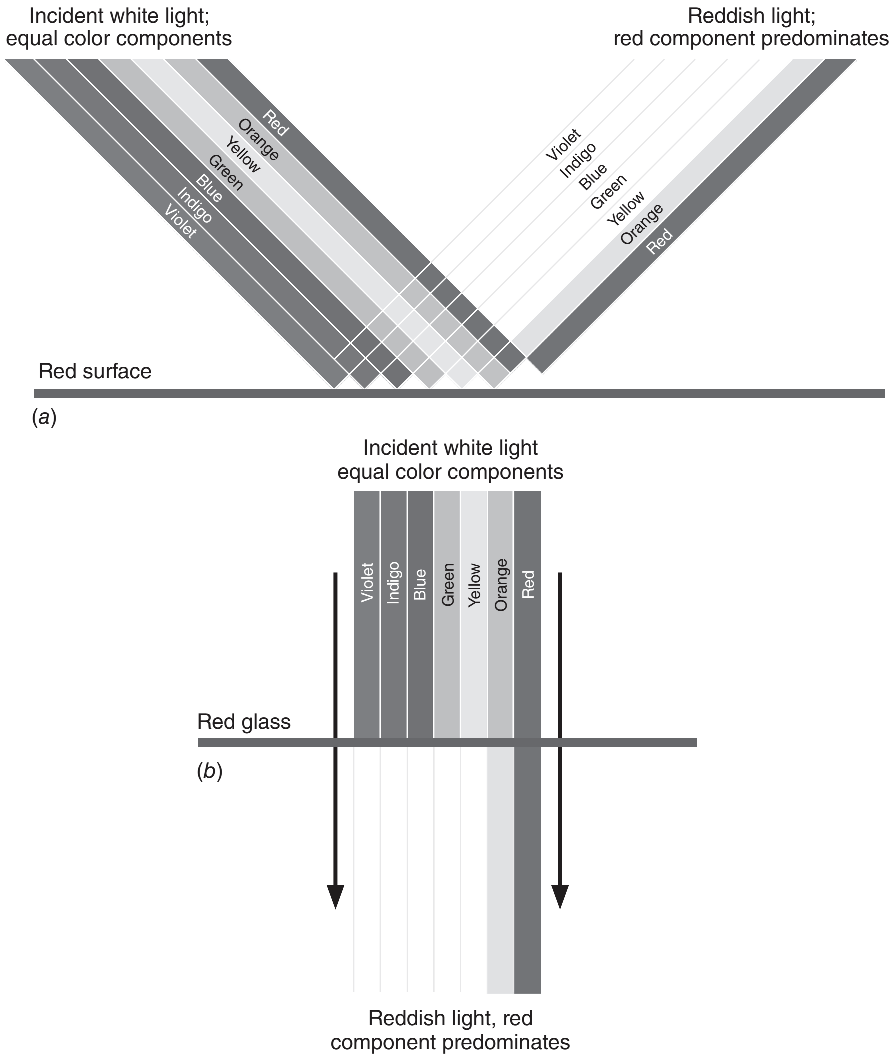


Fig. 13.41 *Selective absorption of materials relative to (a) reflected light and (b) transmitted light.*

to as *value* and saturation as *chroma*; thus, a color is defined by hue, value, and chroma. The brilliance (value) of a pigment or coloration is related to its reflectance to white light—that is, the higher the brilliance or value, the higher the reflectance (as might be expected when one considers that white and black are the poles of brilliance). Chroma or saturation may be thought of as either the difference from gray, or the purity of the color. Spectral colors have 100% purity and therefore maximum chroma.

When white is added to a pigment, it produces a *tint*; adding black produces a *shade*. When pigments are mixed to produce a particular color, the color is created by a subtractive process: Each pigment absorbs certain proportions of full-spectrum white light, but, when mixed, the absorptions combine to subtract (absorb) various colors of the white spectra—leaving only those colors that finally constitute the hue, value, and chroma of the pigment. This subtractive effect is also utilized when producing colors by filtering white light. Each filter selectively absorbs component colors, transmitting only the component desired. Thus, a blue filter transmits only blue, and so on (see Fig. 13.41*b*). Conversely, when lights of the three primary colors—red,

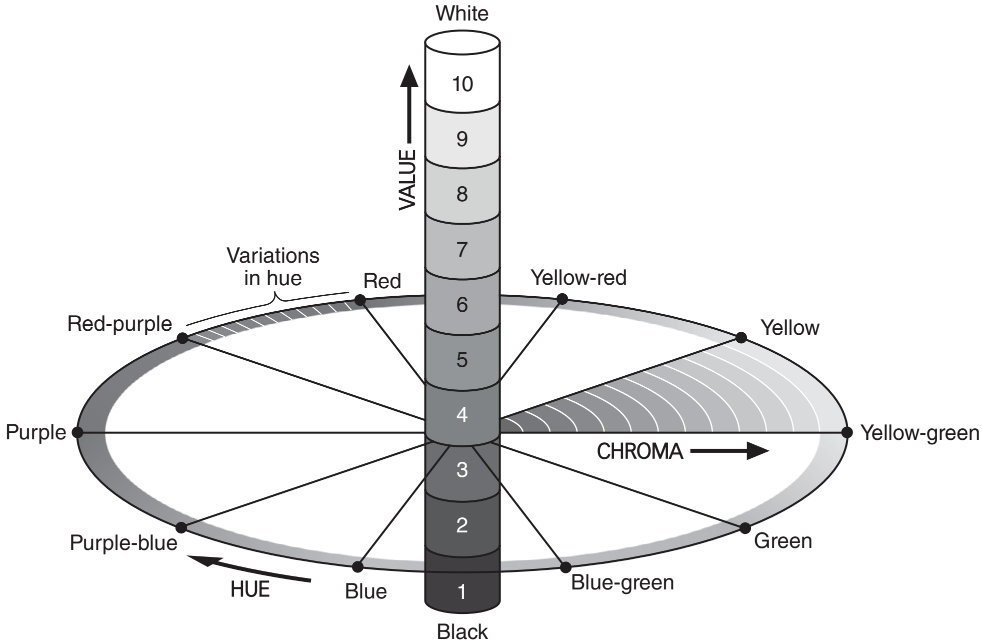


Fig. 13.42 *The Munsell Color System defines a color by three characteristics: hue (color), chroma (saturation), and value (grayness).*

green, and blue—are combined, they form white by an additive process (Fig. 13.43).

The additive and subtractive primary colors are complementary; they combine to give a white or neutral gray, respectively. Thus, red and blue–green, blue and yellow, and green and magenta are complementary. Therefore, if a red object is illuminated with blue–green light, the object's color appears gray because the red pigment absorbs the blue–green and reflects nothing—hence, gray. This accounts for the once common "lost red car" in parking lots illuminated with clear mercury lamps (such lamps having a characteristic blue–green color). Today, this phenomenon is rarely observed, since clear mercury lamps have fallen into disuse in favor of metal–halide and sodium lamps.

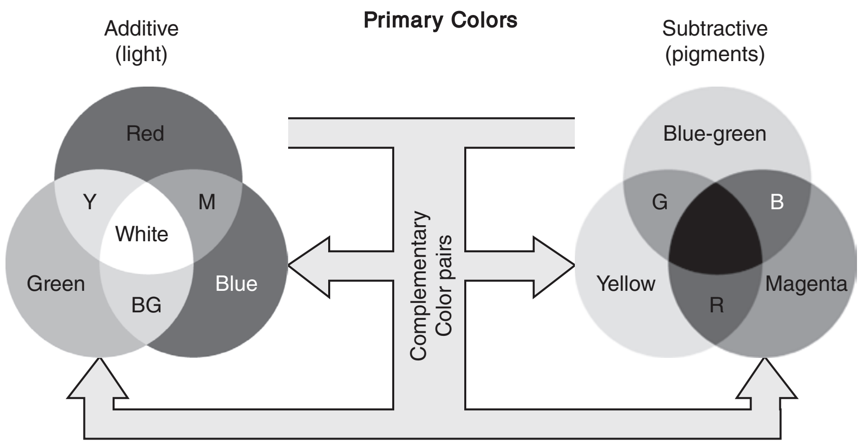


Fig. 13.43 *Primary and complementary colors. Complementary color pairs are shown by arrows. Pigments form color by an absorptive (subtractive) process; colored lights form colors by an additive process.*

13.25 REACTIONS TO COLOR

Light of a particular hue (other than white) is rarely used for general illumination except to create a special atmosphere. When a space is lighted with colored light, the eye adapts by a phenomenon known as *color constancy* so that it can, to a considerable degree (depending on the chromaticity of the light), recognize colors of objects despite the spectral quality of the illuminant. Thus, even when wearing heavily tinted sunglasses, we can still distinguish the color of objects quite easily. Indeed, after only a very short while, we no longer notice the green, yellow, blue, amber, or other color cast caused by the tinted lenses. However, the eyes do become more sensitive to the missing colors that would make up white light. This phenomenon can be used to make meat look redder on a butcher's counter by using blue-rich, red-poor, cool white lighting in the remainder of the store.

A similar phenomenon occurs when the eye is exposed to a monochromatic scene, where the chromaticity is due to the coloration of the objects rather than the illumination. The eye in such a situation becomes sensitized to the complementary color; thus, if after looking at a green surface one shifts one's gaze to a white surface, one sees the complementary red color. Returning to our meat market, the use of green paint on the walls also enhances the redness of the meat. This effect in reverse also partly accounts for the extensive use of green for paints, linens, gowns, and so on, in operating rooms. The eyes of surgeons and nurses, when diverted from the redness of the surgical area, are more comfortable with a green background than with a white one.

By a process known as *lateral adaptation*, the apparent color of an object changes when the background color is changed. Thus, a green object looks somewhat blue–green on a yellow background because the eye is supplying the complementary color to yellow—that is, blue. Similarly, the same green object looks slightly yellow–green when on a blue background, due to the eye supplying the yellow.

The apparent brightness of a color is a function of its hue, in that light colors appear lighter than dark colors even when measured luminance is the same. Thus, spaces may be defined by color within an area of equal illumination. Also, all colors tend to appear less saturated—that is, they appear "washed out"—when illumination is high. Thus, pigments of high saturation (chroma) must be used in well-lit spaces if they are to be effective, although extensive use of saturated colors is generally best avoided.

Other well-known psychological effects of colors are the perceived coolness of blues and greens, and the perceived warmth of reds and yellows. Thus, cool colors might well be used in a display of winter wear, and warm colors in a display of summer wear. Red and yellow are also considered "advancing" colors because objects lit with them are perceived as advancing toward the observer—giving the appearance that they are becoming larger. The opposite effect is noted with blue and green, accounting for their being known as "receding" colors.

A practical, energy-saving application of these color phenomena would be to use warm colors to compensate somewhat for lowered thermostats in the winter, and cool colors for the opposite effect in summer. How to accomplish this without the expense of repainting twice a year is left to the ingenuity of the architect and interior designer. In an atmosphere designed to be calm and restful, greens should generally predominate either in illuminant color, object color, or both—except in eating areas, which should be lighted with reds and yellows because cool colors are generally unappetizing. Yellows and browns emphasize motion sickness, whereas blues and greens tend toward the reverse. Warm, saturated colors produce activity; conversely, cool, unsaturated colors are conducive to meditation. Cool colors also seem to shorten time passage and are well applied in areas of dull, repetitive work.

A further discussion of color control, illuminant colors, color measurement, and color matching is found in the following sections dealing with the spectral energy distribution of sources, and the color rendering index.

13.26 CHROMATICITY

The CIE color system is the internationally accepted standard for designating illuminant color. In this system, the relative proportions of each of the three primary additive colors (red, green, and blue) required to produce a given illuminant color are calculated. These values are called the *tristimulus values* for that color and are designated by capital letters: X (red), Y (green), and Z (blue). See Fig. 13.47 for an example of a chromaticity diagram.

13.27 SPECTRAL DISTRIBUTION OF LIGHT SOURCES

In addition to providing sufficient light of adequate quality, the lighting designer must be concerned with the spectral content of the selected illuminant, because perceived object color depends heavily on the illuminant. As discussed earlier, perceived object color is the result of selective absorption and reflection of components of the illuminating light by the pigments of the object being viewed. It is therefore necessary that the *illuminant* contain the color of the *object* in order for us to see the object's color. It is not so obvious that the relative energy of an illuminant at a particular wavelength determines the saturation and brilliance with which we see a color. To understand this, refer to Fig. 13.44. In graphic

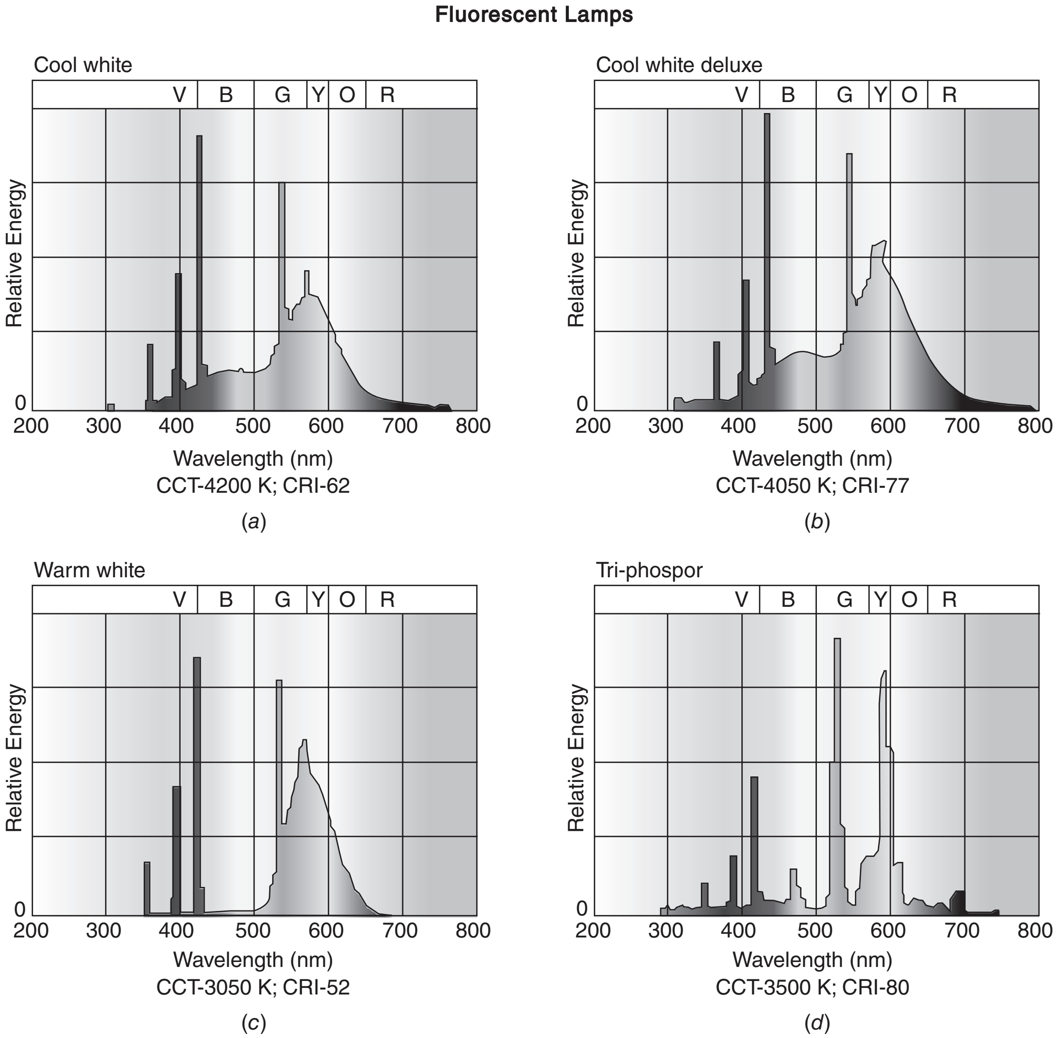


Fig. 13.44 *Spectral energy distribution of several fluorescent lamp types with their correlated color temperatures (CCT) and color rendering indices (CRI). The curves are not truly continuous, but consist of individual color lines; they are shown connected for simplicity. Because only a radiating blackbody has a true color temperature, a source with mixed color illuminants is assigned a CCT, which is the temperature of a blackbody radiator whose chromaticity most nearly matches that of the light source. (These graphs are generic and show patterns of wavelength distribution; consult manufacturers' data for output spectra for a specific lamp.)*

form, the relative spectral energy distributions of a few common light sources have been plotted (as a function of wavelength—that is, color). If we compare the graphs in Figs. 13.44*a* and 13.44*c*, which show the spectral content of two of the most common light sources—cool white and warm white fluorescent lamps, respectively—we note that the principal difference lies in the amount of blue in their spectrum. As a result, a blue object will be bright under cool white light, and dull (grayed) under warm white light. The situation is more pronounced with the standard high-pressure sodium lamp (Fig. 13.45*c*), compared to the clear metal–halide lamp (Fig. 13.45*b*). A blue object will appear gray under the sodium lamp, whereas under the metal–halide lamp its blue color will show clearly.

This concern for perceived object color, which relates not only to furnishings but also to paints and prefinished construction materials such as carpets or floor tiles, is quite properly in the province of the architect and lighting designer, who in turn must possess the knowledge and information necessary to make the appropriate choices of both illuminant *and* object color. Spectral composition graphs of the types shown in Figs. 13.44 through 13.46 are available from manufacturers for all light sources, and they should be examined when considering the characteristics of a particular light source.

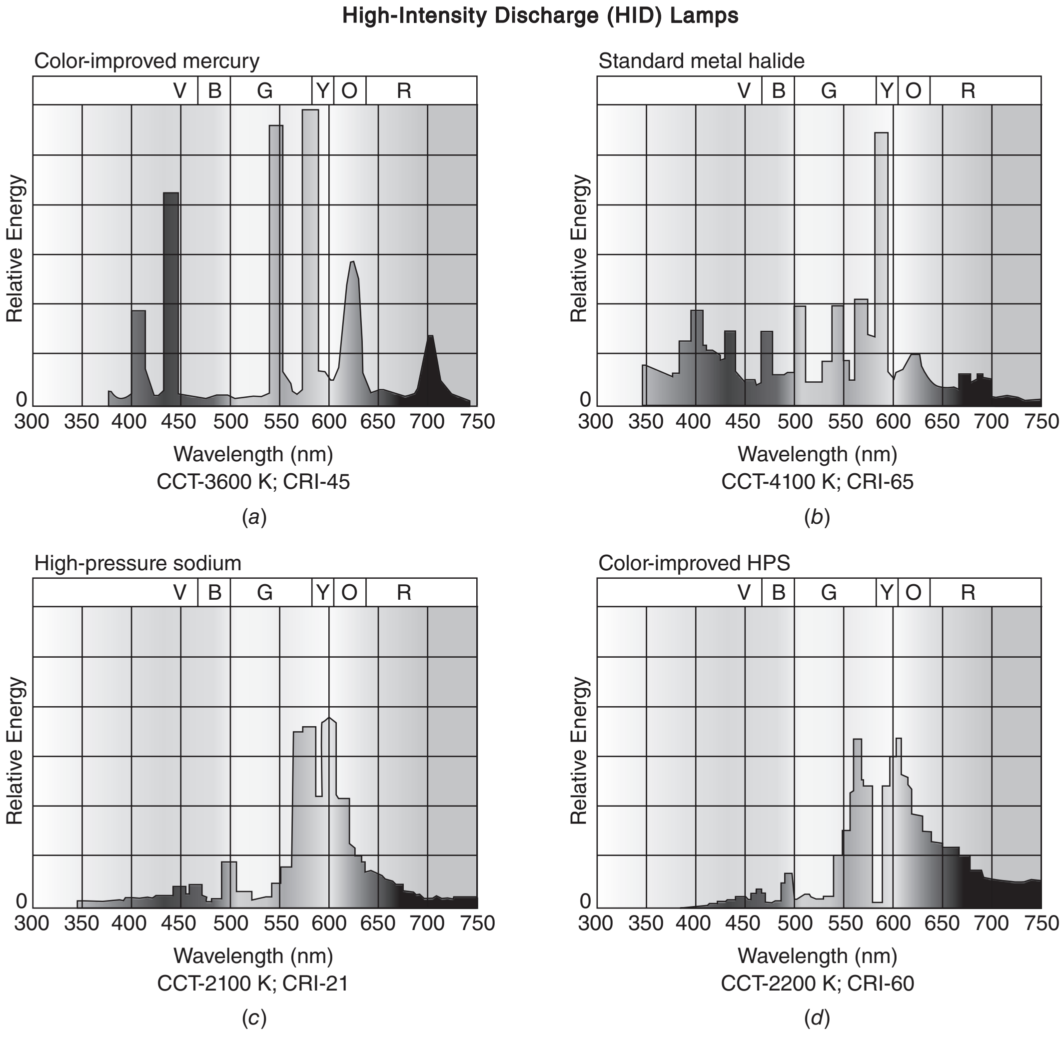


Fig. 13.45 *Spectral energy distribution of typical high-intensity discharge (HID) lamps with their CCT and CRI. (These graphs are generic and show patterns of wavelength distribution; consult manufacturers' data for output spectra for a specific lamp.)*

One of the best ways to compare illuminants is first to expose a dull white surface to the illuminants—side by side, but separated by an opaque divider—in order to get an impression of the illuminant color, and then expose a series of colored chips—again, side by side—to see which colors are brightened and which are grayed. The intensity of illumination also influences the appearance of colors, and it must be considered in choosing object colors. As intensity is increased, reflection increases, particularly with pale tints (high value) that contain much white pigment and thus tend to wash out color. Therefore, with high-intensity lighting, saturation of colors should be high for true, brilliant color rendition.

Refer now to Fig. 13.46. Note from diagrams *b*, *c*, and *d* that the spectrum of a light source that produces light as a result of heating is continuous. Sunlight is equal in spectrum to a blackbody radiator at 5500 K; north light is equal to one at about 8000 K to 10,000 K; a 500-W incandescent lamp is approximately equal to one at 2850 K—and so on.

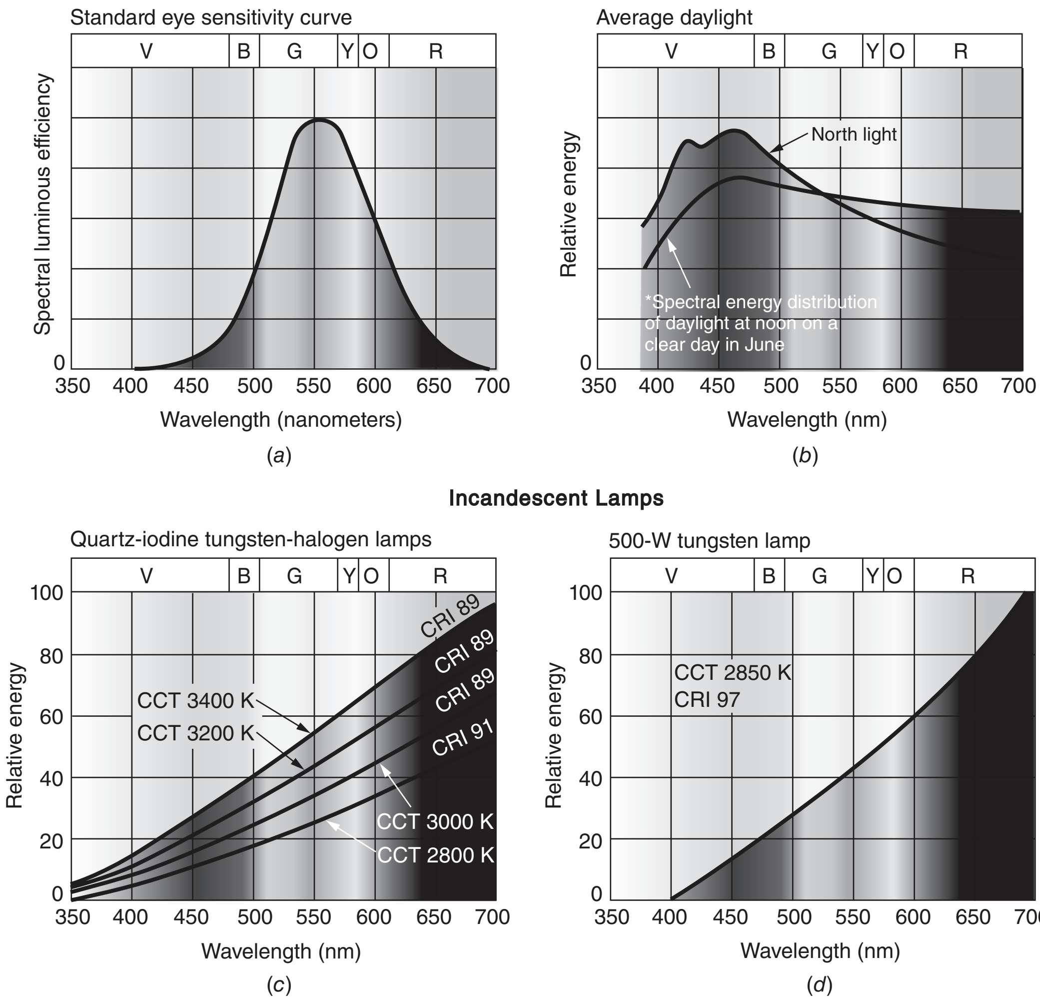


Fig. 13.46 *(a) Standard photopic (cones) eye sensitivity curve. Note that maximum sensitivity occurs in the daylight range of 500–750 nm. (b) Spectral energy distribution of two specific types of daylight. North light, with a color temperature of 8000 K to 10,000 K, peaks in the blue range, whereas noon daylight contains all spectral colors in roughly equal proportions. (c) Tungsten–halogen lamps are incandescent light sources and therefore contain all spectral colors. As wattages increase, the color changes from orange–red to white, and the CRI drops slightly. (d) A simple filament-type incandescent lamp is very close to being a blackbody radiator (i.e., its actual temperature and CCT are almost the same). This is indicated by its high CRI (97).*

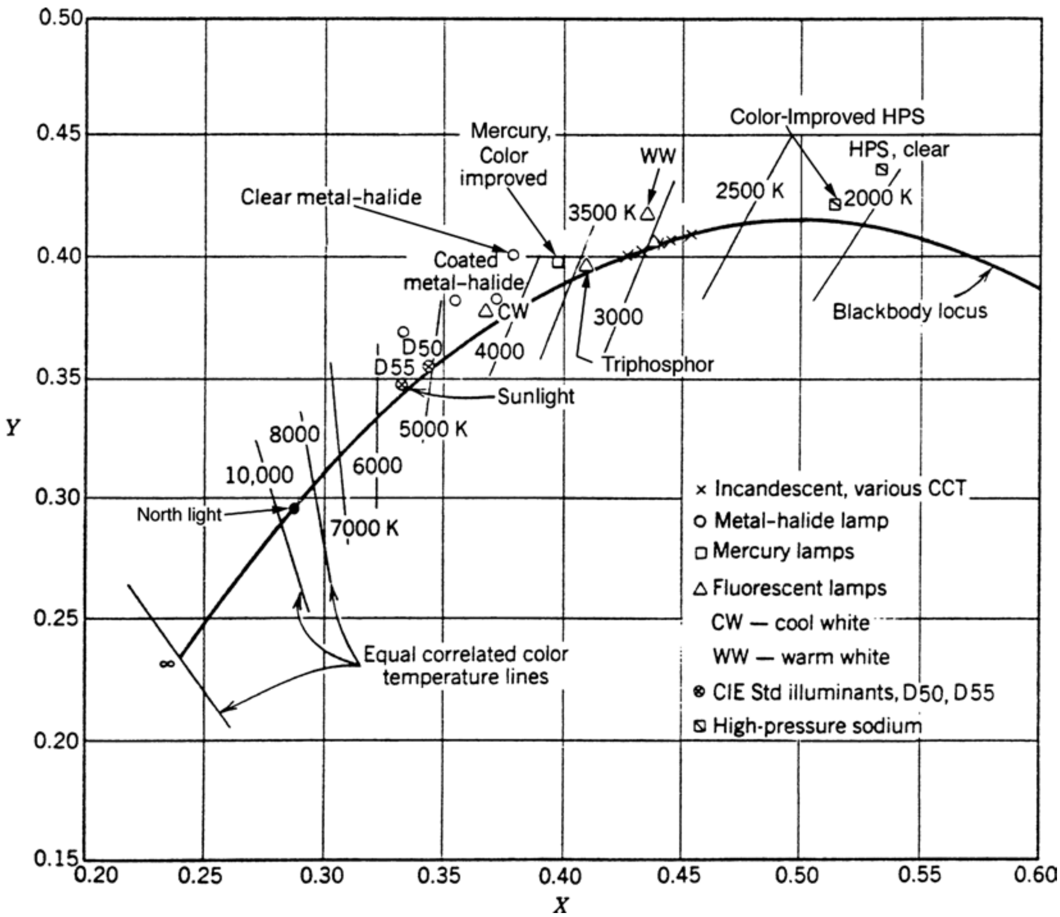


Fig. 13.47 *Portion of a chromaticity diagram showing the relation of common illuminant chromaticities to that of the blackbody locus. Illuminants whose coordinates fall on the same line crossing the blackbody locus have the same CCT but may have entirely different component colors.*

If the spectrum of a blackbody radiator is plotted on a chromaticity diagram, its locus is a continuous curved line, as seen in Fig. 13.47. The chromaticity of all true blackbody radiators falls exactly on this line, with the location depending on temperature. Daylight, for most purposes, falls on this locus, although because of selective atmospheric absorption and other phenomena, it is actually slightly off. Incandescent lamp chromaticity is very close to this locus because it is also a heat-light radiator.

A source that produces light by means of individual phosphors can also have chromaticity on this locus if the phosphors are selected to produce a continuous spectrum similar to that of a blackbody radiator. Thus, we see in Fig. 13.47 that triphosphor fluorescent lamps (Fig. 13.44*d*) and metal–halide lamps (Fig. 13.45*d*) have spectral components over the entire spectrum, yielding chromaticities fairly close to the blackbody locus. For other sources, the CCT is established by their chromaticity locus in relation to the diagonal lines crossing the blackbody locus, as seen in Fig. 13.47. Each of these lines is isothermal—that is, all chromaticities on it have the *same CCT*. Thus, the reader can see that two sources with widely differing spectral content and therefore object color rendering can have the same CCT.

13.28 COLOR RENDERING INDEX

Color rendering is defined as the degree to which perceived colors of objects, illuminated by a test source, conform to the colors of the same objects as illuminated by a reference source. The *color rendering* *index* (CRI) of a source is a two-part concept, comprising a color temperature that establishes the reference standard, and a number that indicates how closely the illuminant approaches the standard. *The standard is always daylight at that color temperature.* Therefore, the CRI of a lamp is really a measure of how closely it approximates daylight of the same color temperature. Two sources cannot be compared unless their color temperatures are equal or quite close. A CRI of 100 indicates an illuminant whose spectral content is equal to daylight of that temperature. CRIs for typical common lamps are given in Figs. 13.44 through 13.46.

Table 13.8 lists the color characteristics of a few of the major sources. An illuminant's own color appearance on a neutral surface depends on its own spectral content, but if the observer is placed in a space illuminated with this source, after a short exposure time the eye becomes adapted to the source color and detects only a degree of whiteness rather than an actual tint.

Where it is necessary to detect small color differences between two objects, a light poor in object color or complementary to the object color should be used at a relatively high illumination level, followed by a light high in object color at the same

TABLE 13.8 Effect of Illuminant on Object Colors

				Colors		
Lamp	**CRI (approximate)**	**CCT (K)**	**Whiteness**	**Enhanced**	**Grayed**	**Notes**
FLUORESCENT						
Warm white	52	3050	Yellowish	Orange yellow	Red, blue, green	
Cool white	62	4200	White	Yellow Orange Blue	Red	
Cool white deluxe	77	4050	White	Green Orange Yellow	Red	
Triphosphor	75	2800	Yellowish	Red Orange	Deep red, blue	
	80	3000	Pale yellowish	Red Orange Green	Deep red	
MERCURY						
Clear	20	7000	Blue–green	Blue Green	Red Orange	Poor overall color rendering
Deluxe	45	3700	Pale purplish	Deep blue, red	Blue– green	Shift over life to greenish
METAL–HALIDE						
Clear	65	4000	White	Blue Green Yellow	Red	May shift to pinkish over life
Phosphor-coated	80	4200	White	Blue Green Yellow	None	Shifts to pinkish over life
HIGH-PRESSURE SODIUM						
Standard	21	2100	Yellowish	Yellow Green	Red, blue	
Color-corrected	60	2200	Yellowish-white	Red Green Yellow	Blue	CRI decreases slightly over life
INCANDESCENT						
Incandescent	99+	2900	Yellowish	Red, orange, yellow	Blue, green	

Fig. 13.48 *Handheld chromaticity meter. Specifically for LED, organic LED, or other types of organic electroluminescence, this chromaticity meter is able to generate a simultaneous reading of illuminance, color temperature, excitation purity, dominant wavelengths, and chromaticity. (Courtesy of Konica Minolta, Inc.)*

illumination level. If this is not possible, two widely different but broad-spectrum illuminants should be used, preferably at the same illumination level. Another technique is the use of a special, fixed-color source. For a full discussion, see the current *IESNA Lighting Handbook*.

It should be remembered in all considerations of color, comparison, matching, and rendering that object color depends on the spectral energy distribution of the light source (illuminant), and therefore any change in the spectral content changes the object's appearance. Two sources of the same color temperature—and, therefore, apparent whiteness—can have quite different spectral content and subsequently render object colors differently. A case in point would be a 3000-K warm white fluorescent tube and an incandescent lamp (500-W photoflood) of approximately the same color temperature. Color temperature is an expression of dominant color, not spectral distribution.

A convenient hand-held chromaticity meter is illustrated in Fig. 13.48. This unit measures the *X*, *Y* coordinates of an illuminant, which can then be plotted on a standard CIE color diagram to determine absolute chromaticity. This is very useful in comparing illuminants to predict the color response and avoid color metamerisms.

References and Resources

Cotton, H. 1960. *Principles of Illumination*. John Wiley & Sons. New York.

The Franklin Institute. *Light and Color*. http://www.fi.edu/color/

IESNA. 1963. "How to Make a Lighting Survey." *Illuminating Engineering*, Vol. 57, No. 2, 87–100.

IESNA. 2011. *IESNA Lighting Handbook*, 10th ed. Illuminating Engineering Society of North America. New York, NY.

International Technologies, *The Light Measurement Handbook*. http://www.intl-lighttech.com/services/light-measurement-handbook/

Lighting Design Lab (Seattle). http://lightingdesignlab.com/

Lighting Research Center. http://www.lrc.rpi.edu/

Murdoch, J. B. 1985. *Illumination Engineering*. Macmillan. New York, NY.

Ross and Baruzzini, Inc. 1975. "Energy Conservation Applied to Office Lighting" (Conservation Paper No. 18). Federal Energy Administration. Washington, DC.

Sampson, F. K. 1970. *Contrast Rendition in School Lighting*. Educational Facilities Laboratory. New York, NY.

United States Census Bureau – State and County QuickFacts, Population, 2012 estimate. http://quickfacts.census.gov/qfd/states/00000.html

CHAPTER 14

Electric Light Sources

CHOOSING LIGHT SOURCES FOR BUILDINGS—WHETHER DAYLIGHT OR ELECTRIC LIGHT (or, more likely, a combination of both)—involves simultaneous lighting and thermal considerations. Because electric lighting in American nonresidential buildings consumes 25% to 60% of the electric energy utilized, any attempt to reduce this quantity must necessarily include integration of the cheapest (insofar as energy is concerned), most abundant, and, in many ways, most desirable form of lighting available—daylight. In designing appropriate lighting systems for buildings, understanding the characteristics of light sources will allow a designer to use them appropriately for energy efficiency and to provide visual and thermal comfort. For resource efficiency, a designer should first optimize daylighting, and then design the electric lighting system to supplement and enhance illuminance, visual comfort, and architectural effect. This chapter describes the characteristics of electric light sources, including the limits and capabilities of each source.

INCANDESCENT LAMPS

14.1 THE INCANDESCENT FILAMENT LAMP

(a) Construction

The standard incandescent lamp consists of a tungsten filament inside a gas-filled, sealed glass envelope. Current passing through the high-resistance filament heats it to incandescence, producing light. Gradual evaporation of the filament causes the familiar blackening of the bulb and eventual filament rupture and lamp failure. Incandescent lamps are available in many bulb and base types, with special designs for particular applications (Fig. 14.1). In order to diffuse the light output, most bulbs are coated inside with white silica, providing almost complete light diffusion at a reduction of approximately 2% to 3% of the light output. Colored light is available from either coated bulbs or bulbs of colored glass.

The incandescent lamp base is the means by which a connection is made to the socket and thereby to the source of electric current. Most lamps are made with screw bases of various sizes, the most common being the medium screw base. General-service lamps of 300 W and larger use a mogul screw base. When lamps are placed in precise reflectors or in lens systems where exact positioning of the filament is important, one of the special bases illustrated in Fig. 14.1 is used.

(b) Operating Characteristics

Critically dependent upon the voltage being supplied, the life, output, and efficiency of a lamp can be markedly altered by even a small change in operating voltage. For example, operating a 120-V lamp at 125 V or 115 V (Table 14.1) affects lumen output and, in particular, lamp life. In installations

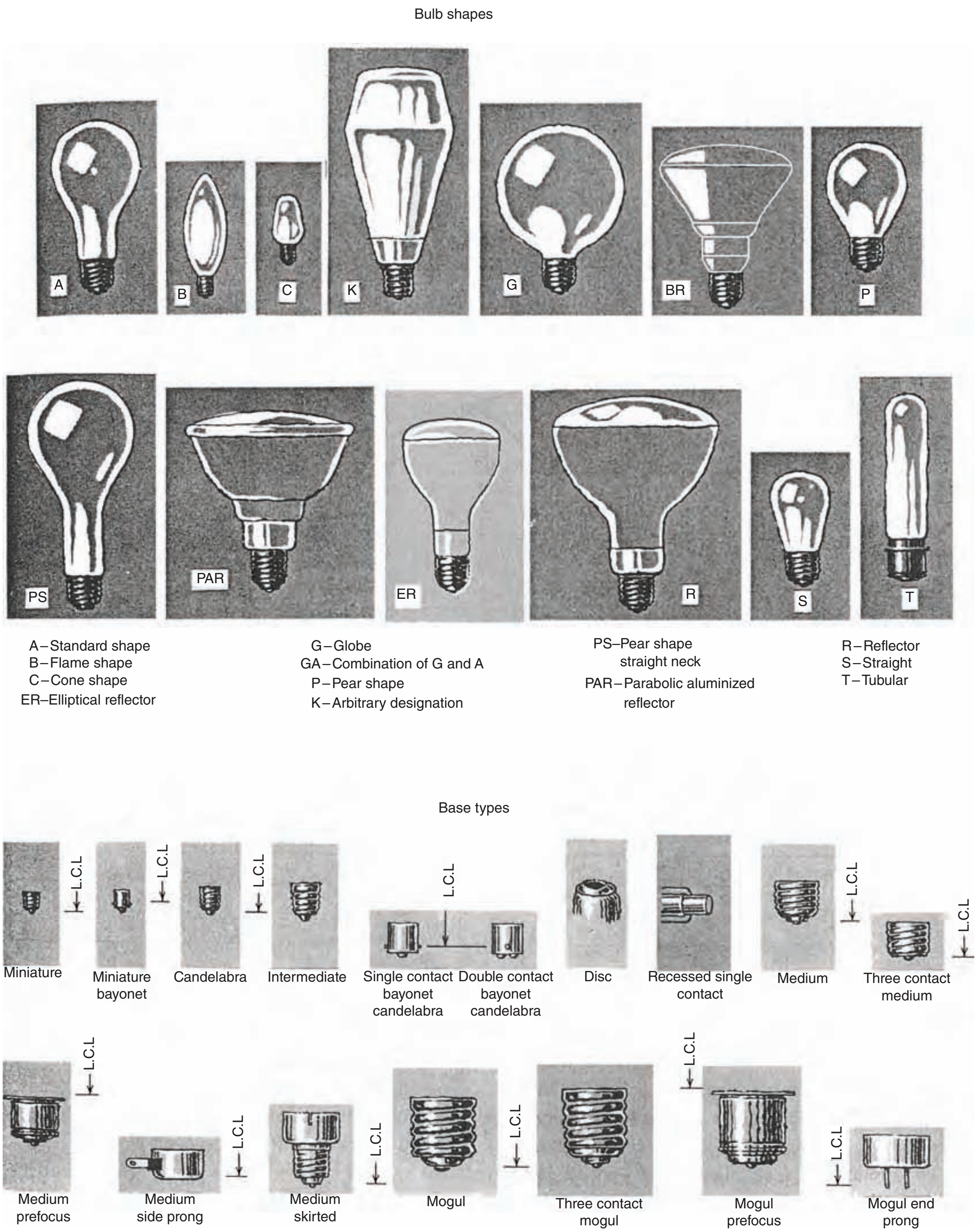


Fig. 14.1 *Common incandescent lamp bulb and base types with nomenclature. The complete bulb nomenclature indicates type and size. The letter is an abbreviation of the shape, and the number is the diameter in eighths of an inch. A PS-52 is a pear-shaped bulb $^{52}/_{8}$ in. (6½ in. [165 mm]) in diameter. A PAR-38 is a parabolic reflector lamp $^{38}/_{8}$ in. (4¾ in. [121 mm]) in diameter.*

TABLE 14.1 Comparison of Operating Characteristics

Operation of Lamps	120-V lamp at 125 V (104.2%)	120-V lamp at 115 V (95.8%)
Amount of light (lumens)	16% more	15% less
Power consumption (watts)	7% more	7% less
Efficacy (lumens per watt)	8% higher	8% lower
Life (hours)	42% less	72% more

where lamp replacement is difficult and/or expensive, and use of an incandescent lamp is appropriate, lamps may be operated slightly under-voltage to prolong life, thereby decreasing the frequency of replacement. Because luminous efficacy (the number of lumens emitted for each watt of electricity used) is decreased by this procedure, and recognizing that energy cost is normally a major consideration over the life of any lighting installation, a detailed life-cycle cost analysis (as per the principles described in Appendix J) should be made by the design professional. Conversely, where lamps are replaced before burnout, using a group replacement system, and initial installation cost per lux and/or energy costs are high, lamps may be operated overvoltage, thereby increasing their output and efficacy but shortening their life. This procedure is normal in sports-lighting installations because of the high installation cost of tower-mounted floodlights, making it mandatory to extract the maximum light from each unit. In stadium installations with yearly lamp operation schedules averaging less than 200 hours, 10% overvoltage operation doubles the light output but still allows a once-a-year, off-season relamping and is therefore a highly economical procedure. Generally, however, it is advisable to operate incandescent lamps at the rated voltage, accepting balanced efficacy, output, and life.

(c) Other Characteristics

1. *Lumen maintenance.* Light output decreases slowly with lamp life as an incandescent bulb blackens. Lamp position (vertical or horizontal) during operation and the resulting bulb temperatures affect this characteristic.
2. *Color.* Incandescent light has a large yellow-red component and is therefore highly flattering to the skin. The spectral content of the light produced by a heated source depends upon its temperature: High-wattage lamps are bluer, low-wattage lamps are yellower. Dimmed lamps give yellow–red light.
3. *Surroundings.* Generally, incandescent lamps are impervious to surrounding heat, cold, or humidity. Starting is completely unaffected by ambient conditions. Bulbs, however, must be appropriately selected if exposure to water is expected.
4. *Luminous efficacy.* Incandescent lamps produce light as a by-product of heat; as a result, they are inherently inefficient. Luminous efficacy increases with wattage. Thus, a 60-W general-service lamp produces 890 initial lumens, or 14.8 lm/W, whereas an A-21 100-W lamp produces only slightly less output than two 60-W lamps, but the higher wattage results in 18% energy savings.

(d) Summary

The principal advantages of incandescent lamps are: low cost; instant start and restart; simple, inexpensive dimming; simple, compact installation requiring no accessories; cheap fixtures; focusability as a point source; high power factor; lamp life independent of the number of starts; and skin-flattering, full-spectrum color. From a human factor perspective, the full-spectrum quality of incandescent light, with higher amounts of light in the red wavelengths, is best for rendering skin tones.

The principal disadvantages are low efficacy (see Table 8.1), short lamp life, and critical voltage sensitivity. Low efficacy means more fixtures and larger heat gain than with more energy-efficient alternative sources. Short lamp life results in high lamp-replacement labor costs. Voltage sensitivity may require careful and expensive circuit design. Also, light concentration at the filament (point source) requires careful fixture design in order to avoid glare and, if undesirable, sharp shadows. Because of its poor energy characteristics, incandescent lamp use should be limited to the following applications:

- Where use is infrequent
- Where there is frequent short-duration use

- Where low-cost dimming is required
- Where the point source characteristic of the lamp is important, as in focusing fixtures
- Where minimum initial cost is essential
- Where its characteristically good color rendering is desired

Specific lamp data for use during design development should be obtained from current manufacturers' literature.

14.2 SPECIAL INCANDESCENT LAMPS

In addition to the tungsten–halogen lamp, which is discussed separately, numerous special types of incandescent lamps are available. Some of the more important types are covered briefly in the following pages.

Rough service and *vibration* lamps are built to withstand rough handling and continuous vibration, respectively. Both conditions are extremely hard on general-service lamp filaments. Neither of these types is intended for general use, and both have lower luminous efficacy than a general-service incandescent.

Extended-service lamps are designed for 2500-hour life. They are useful in locations where maintenance is irregular and/or relamping is difficult. Such lamps are specifically designed for slightly higher voltage than that which is applied, and therefore efficacy is reduced. So-called long-life lamps—which are guaranteed to burn for 2, 3, or 5 years—are actually just lamps designed for higher voltages than those listed. As they normally sell at a high cost and are very inefficient, their use is seldom advisable. Before using such lamps, a life-cycle cost comparison, including the cost of lamps, energy, and relamping, should be made.

(a) Reflector Lamps

These are made in "R," "BR," "ER," and "PAR" shapes (see Fig. 14.1). They contain a reflective coating on the inside of the glass envelope that gives the entire lamp accurate light-beam control. Many reflector lamp types are available in narrow or wide beam design, commonly called *spot* and *flood*, respectively. R lamps are generally made in soft glass envelopes for indoor use, whereas PAR lamps are hard glass, suitable for exterior application. When using R and PAR lamps, the fixture acts principally as a lampholder since beam control is built into the lamp. These lamps have an improved reflector design that increases their efficiency.

TABLE 14.2 Minimum Required Efficacy of R and PAR Lamps

Nominal Lamp Wattage (W)	Minimum Efficacy (lm/W)
40–50	10.5
51–66	11.0
67–85	12.5
86–115	14.0
116–155	14.5
156–205	15.0

A number of incandescent reflector lamps are essentially obsolete in the U.S. because of ongoing rounds of energy legislation. Luminous efficacy limits as shown in Table 14.2 are in place. All major manufacturers produce incandescent reflector lamps that meet current legislative requirements. Among these are elliptical reflector (ER) and bulge reflector (BR) lamps that use a more efficient reflector design.

(b) Energy-Saving Lamps

Major national energy legislation including the National Appliance Energy Conservation Act of 1987, the Energy Policy Act of 1992 (and its 2005 update), and the comprehensive energy legislation passed by the U.S. House of Representatives and U.S. Senate in 2003 and again in 2007 have created requirements to conserve lighting energy. The American Council for an Energy-Efficient Economy (ACEEE), the U.S. Department of Energy (DOE), and the Environmental Protection Agency (EPA) have developed and support lighting energy efficiency programs, new research, and initiatives. For example, the ENERGY STAR® program (http://www.energystar.gov/), established by the EPA in 1992 to improve and provide energy-efficient products (appliances, lighting, heating and cooling equipment) and practices, is aimed at reducing emissions from power plants, avoiding the need for new power plants, and reducing energy bills. ENERGY STAR encourages every U.S. household to change the five fixtures used most often at home (or the lamps in them) to ENERGY STAR–qualified lighting to save more than $60 every year in energy costs. If every household did this, it would keep more than 1 trillion pounds of greenhouse gases out of the air—a $6 billion energy savings equivalent to the annual output of more than 21 power plants.

All major manufacturers produce a line of energy-saving lamps. Energy-efficient lamps are frequently known by trademarked names. They are rated at a lower wattage than that of the standard lamps they are intended to replace and are generally more efficient. Any additional first cost should be analyzed by a life-cycle cost analysis and the payback period calculated. The designer will find that an effective control system is often more economically attractive than low-wattage lamps and that energy-saving incandescent lamps are primarily useful in retrofit work.

14.3 TUNGSTEN–HALOGEN (QUARTZ–IODINE) LAMPS

This lamp type, illustrated in Fig. 14.2, is conceptually similar to the standard incandescent lamp in that it produces light by heating a filament. It differs in that a small amount of halogen gas (iodine or bromine) is added to the inert gas mixture that fills a small capsule, constructed of quartz glass, surrounding the filament within the bulb of the lamp. This addition results in retardation of filament evaporation, which is the usual cause of incandescent lamp failure, and thereby extends lamp life (Fig. 14.3).

Although the tungsten–halogen lamp has only slightly higher luminous efficacy than an equivalent standard incandescent lamp, it has the advantages of longer life, lower lamp lumen depreciation (98% output at 90% life), and a smaller bulb for a given wattage (see Fig. 14.2). The last characteristic is due to the high temperature required by the halogen cycle, which in turn requires a compact, high-temperature filament. As a result, the lamp is effectively a point source, making it ideal for use in precision reflectors. Indeed, it is in this area, as discussed later, that most of the recent developments in tungsten–halogen lamp technology have occurred.

Due to the lamp's high filament temperature, the bulb envelope is generally made of quartz or a special high-temperature glass, which can withstand high temperatures better than glass; this, in turn, gave rise to an alternative name, *quartz–iodine,* that is sometimes applied to this lamp type. Another

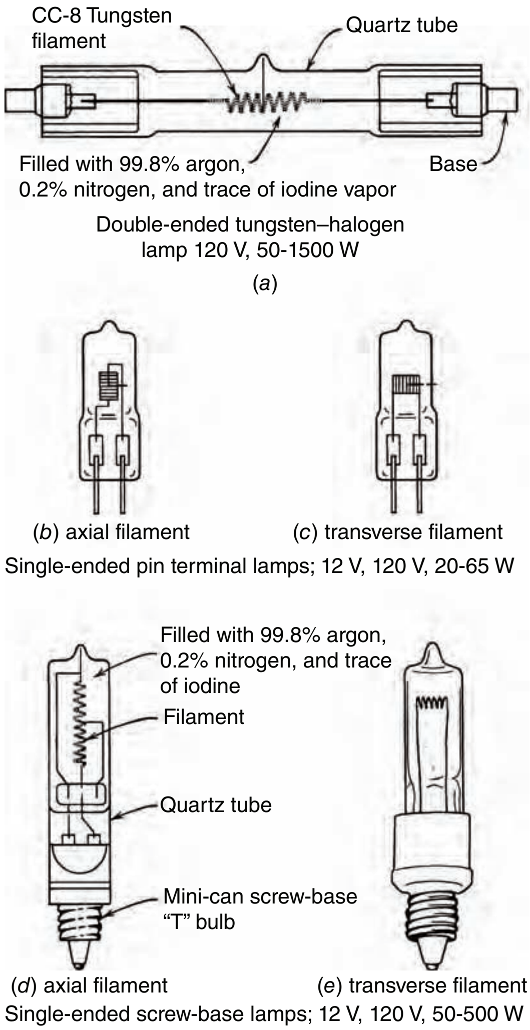


Fig. 14.2 *Common tungsten–halogen lamps are available in a variety of designs.*

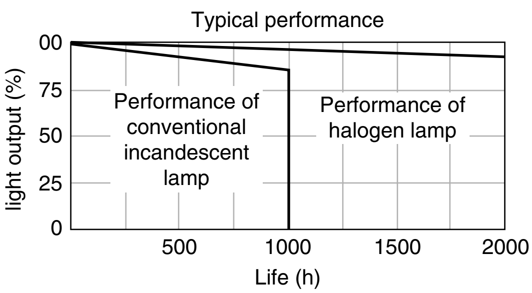


Fig. 14.3 *The self-regenerative halogen cycle slows the evaporation of the tungsten filament, and consequently lowers light loss depreciation and lengthens the lamp life compared to a standard incandescent lamp.*

result of high filament temperature is that the gas pressure inside the quartz envelope is elevated—the lamps have been known to rupture violently, spraying hot quartz fragments over a wide area. As a consequence, all manufacturers now provide a cautionary notice with their lamps. The wording varies but essentially states that due to the possibility of rupture, lamps should be handled carefully, guarded against abrasion and overvoltage operation, and, most importantly, adequately shielded or screened. The shield can be a reflector cover, a fixture lens, a screen, or other device that will contain hot flying fragments in the event that a lamp shatters or high temperatures cause a fire hazard.

A number of standards organizations and professional societies have adopted and published cautionary notices, including *The Lighting Handbook* (IESNA), ANSI Standard C78.1451-2002, the Canadian Standards Association, and the International Electrotechnical Commission (IEC). Exceptions to these precautions exist when a lamp is protected by encapsulation inside a sealed envelope. Such encapsulated construction is now common in R, PAR, MR, and modified A-lamp shapes. These encapsulated lamps are intended for direct replacement of standard incandescent lamps of the same bulb shape.

Other halogen lamp characteristics are similar in all respects to those of the standard incandescent lamp. Color temperature ranges between 2000 K and 3400 K; spectral energy distribution is typical of blackbody radiation, and dimming characteristics are similar to those of standard incandescent lamps.

14.4 TUNGSTEN–HALOGEN LAMP TYPES

The basic tungsten–halogen lamp is a small gas-filled quartz tube, as shown in Fig. 14.2. Because the lamp

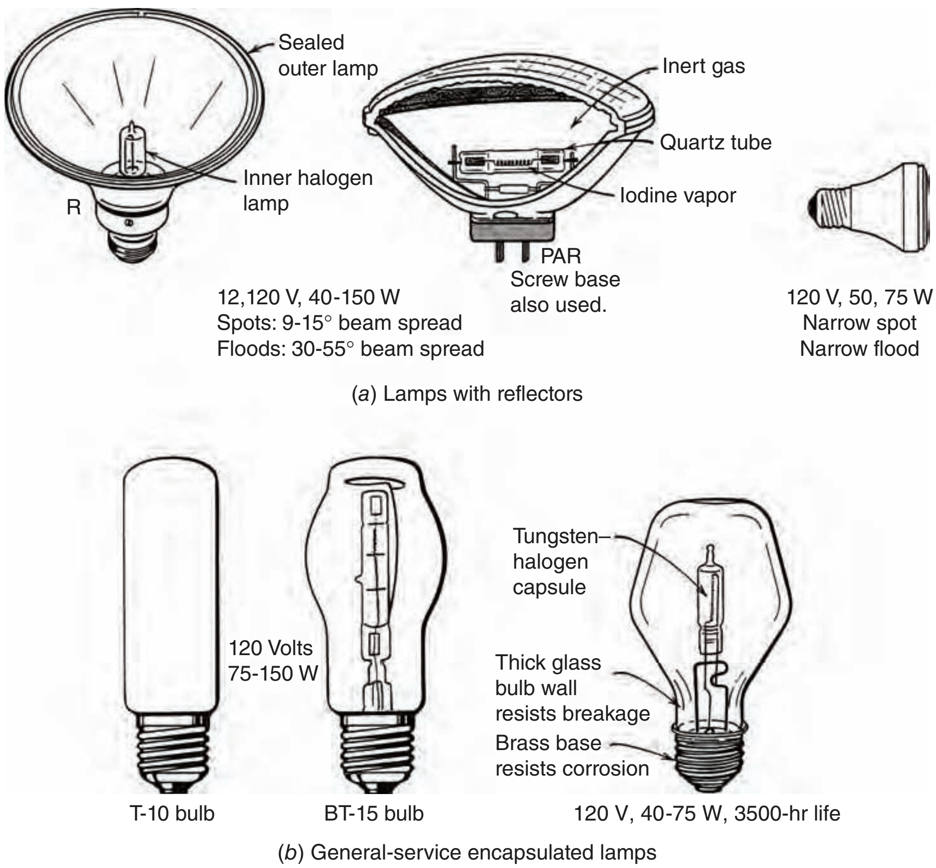


Fig. 14.4 *Tungsten–halogen lamps can be mounted in a variety of ways inside an enclosing glass envelope. (a) Lamp is used either horizontally or vertically to the reflector or (b) used without a reflector in a protective glass envelope and an Edison medium screw base.*

must be used with some sort of reflector, it is manufactured with different terminations to suit the fixture reflector or secondary lamp envelope in which it is placed. All the lamp types shown in Fig. 14.2 can be used where lamp-only replacement is intended, such as in floodlights or reflector fixtures, by using appropriate bases—slide contacts for double-ended lamps, screw bases for screw-base lamps, and special ceramic pinhole bases for pin-type lamps.

(a) Encapsulated Lamps

These lamps (Figs. 14.4 and 14.5) are sealed units intended for direct replacement of either a corresponding distribution-type of incandescent lamp in the case of reflector units, or general-service incandescent lamps for reflector-less units. As a sealed unit, the halogen lamp is not replaceable, and the entire unit is discarded on burnout. Reflector units are available in a wide variety of beam patterns detailed in manufacturers' catalogs. Typical data are given in Fig. 14.6.

Reflector lamps are also available with a variety of filters: so-called cool lamps that direct much of the radiant heat out through the back of the lamp; high-efficiency units that reflect and concentrate

Fig. 14.5 PAR halogen lamps with standard medium screw bases in sizes PAR 16, 20, 30, and 38 with a short or elongated lamp neck. Lamp wattages range from 45 to 90 W. (Courtesy of Philips Lighting Co.)

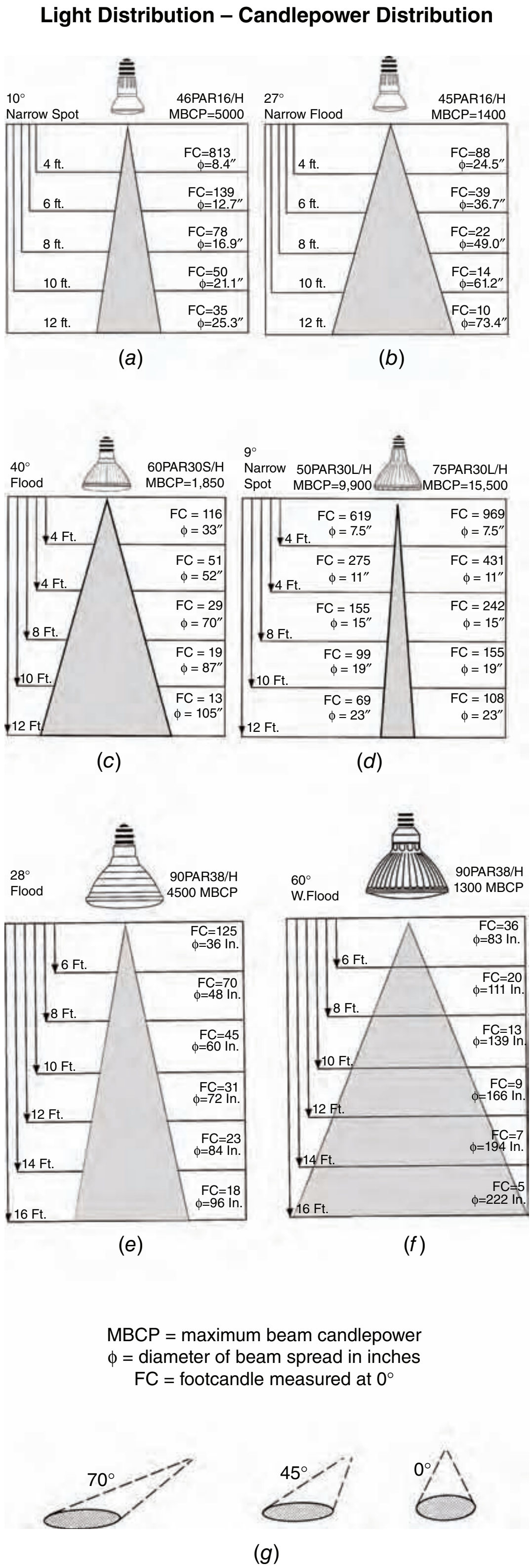


Fig. 14.6 Typical PAR halogen lamp data. The beam of the PAR lamp is conical in shape. Each type of PAR lamp has a distinct illumination pattern (a–f) that varies in size and light intensity, depending on the angle at which the lamp is aimed and its distance from the area illuminated. (g) The round lighting pattern changes to oval or elliptical when the lamp is aimed at an angle, making illuminance calculations much more complex. Data in (a)–(f) courtesy of Philips Lighting Co.

radiant heat back onto the lamp filament; lamps with ultraviolet (UV) filters for use in displays of UV-sensitive objects; and others. For complete design information, access to current manufacturers' catalogs is a necessity.

(b) MR-16 Precision Reflector Units

Miniature single-ended 12-V lamps of 2-in. (50-mm) diameter (and smaller), with multifaceted dichroic (heat-ejecting) reflectors and a bi-pin base, have found very wide acceptance in all types of display and accent lighting applications. These reflector units are illustrated in Fig. 14.7. They essentially constitute an entire lighting fixture, like R and PAR lamps, requiring only a base for electrification. The lamps are known by the generic name *MR-16*, after an early 2-in. (50-mm) diameter model, although each major manufacturer utilizes its own trade name. A multi-mirror-faceted dichroic reflector

(*a*)

FOOT CANDLE CONES

TRU-AIM TITAN™

10° NSP

Distance from Source (in ft.)	Diameter (in ft.)	Center FC 20W	35W	50W	65W
0′					
3′	0.5	556	922	1278	1556
6′	1.0	139	231	319	389
9′	1.6	62	102	142	173
12′	2.1	35	58	80	97
15′	2.6	22	37	51	62

25° NFL

Distance from Source (in ft.)	Diameter (in ft.)	Center FC 50W	65W
0′			
3′	1.3	356	444
6′	2.7	89	111
9′	4.0	40	49
12′	5.3	22	28
15′	6.7	14	18

40° FL

Distance from Source (in ft.)	Diameter (in ft.)	Center FC 20W	35W	50W	65W
0′					
3′	2.2	78	139	222	233
6′	4.4	19	35	56	58
9′	6.6	9	15	25	26
12′	8.7	5	9	14	15
15′	10.9	3	6	9	9

60° VWFL

Distance from Source (in ft.)	Diameter (in ft.)	Center FC 20W	35W	50W	65W
0′					
3′	3.5	39	72	111	117
6′	6.9	10	18	28	29
9′	10.4	4	8	12	13
12′	13.9	2	5	7	7
15′	17.3	2	3	4	5

(*b*)

Fig. 14.7 *(a) Photo of a particular type of MR-16 lamp. (b) Typical illumination cones for the lamp shown in (a). Abbreviations: NSP, narrow spot; NFL, narrow flood; FL, flood; VWFL, very wide flood. (Courtesy of Osram-Sylvania Products, Inc.)*

produces a "cool" precision light beam by ejecting approximately two-thirds of the lamp heat (long-wave radiation) through the back of the reflector. Luminaires must provide adequate means to dissipate this heat to avoid early lamp failure or creation of a fire hazard. The lamps are rated from 20 to 75 W. Beam characteristics of a few MR-16 lamps are given in Fig. 14.7.

GASEOUS DISCHARGE LAMPS

Lamps in this category include fluorescent and high-intensity discharge (HID) lamps (mercury-vapor, metal–halide, high-pressure sodium), which function by producing an ionized gas in a glass tube or container rather than heating a filament. Discharge lamps are known for their long life and high luminous efficacy. This section describes the function of a ballast and the various types of gaseous discharge lamps.

14.5 BALLASTS

All gaseous discharge lamps require a ballast to trigger the lamp with a high ignition voltage and to control the amount of electric current for proper operation. There are two kinds of ballasts: magnetic and electronic. A magnetic ballast uses coiled wire and creates magnetic fields to transform voltage but does not change the frequency of the power to the lamp—in the United States, 60 Hz. An electronic ballast uses solid-state components to transform voltage. The frequency of the power changes from 60 Hz to 20,000 Hz, or higher, depending on the ballast, and this generally functions more efficiently and cooler than electromagnetic fields. The frequency change also greatly reduces any flicker in the lamp due to burn-in or improper power.

The ballasts discussed in this section primarily apply to fluorescent lamps. Refer to manufacturers' information for details regarding HID ballasts. Correct matching of ballast to lamp is critical to successful lamp operation.

A ballast has several primary functions:

- Supplies the voltage to break down the gas between the electrodes of arc lamps and initiate starting
- Supplies the voltage and current to heat the electrodes to allow a low-voltage, high-current arc mode to develop (referred to as glow-to-arc transition)
- Supplies enough current to heat and evaporate the light-emitting components after an arc has been established; provides enough sustaining voltage to maintain the arc during warmup and operation
- Limits lamp current once all the evaporable materials have reached thermal equilibrium

Organizations involved with ballast standards and testing include:

ANSI—American National Standards Institute: Oversees standards on a national level

CBM—Certified Ballast Manufacturers: A group of fluorescent ballast manufacturers who produce ballasts that conform to certain ANSI specifications

ETL—Electrical Testing Laboratories, Inc.: A private, independent organization and recognized authority in measurement and testing of lamps and lighting equipment

UL—Underwriters Laboratories, Inc.: An independent, nonprofit organization that certifies electrical products to ensure public safety from fire

In the United States, ballasts should be UL labeled and CBM/ETL certified (for a limited number of fluorescent ballasts). The UL label ensures intrinsic safety, CBM establishes high-quality design criteria, and ETL tests ballasts to determine that design standards have been met.

(a) Ballast Characteristics

Because of the considerable energy that is lost in inefficient ballasts, manufacturers and standards organizations have established criteria by which ballast energy efficiency can be judged. These characteristics allow comparisons of lighting system operation and performance parameters.

Ballast Factor. Ballast factor is the measured ability of a ballast to produce light from a connected lamp. It is the ratio of the light output of a lamp when operated on a tested ballast, to the light output of the same lamp when operated by a standard laboratory reference ballast (using ANSI test procedures). Ballasts with extremely high or low ballast factors can reduce lamp life because of inconsistencies in lamp current. ANSI Standard C82.11 prescribes a minimum ballast factor for CBM certification for a certain number of ballast types. A ballast may have different ballast factors for different lamps—for example, one ballast factor for operating standard lamps, and another for operating energy-saving lamps. A lamp with a low ballast factor uses less energy, but light output is also less. A lamp with a high ballast factor uses more energy, but provides more light output. Energy savings with high ballast factors may be achieved by using lower-wattage lamps and fewer fixtures. Ballast factor is not a measure of energy efficiency. Although a lower ballast factor reduces lamp lumen output, it also consumes proportionately less input power. Therefore, careful selection of a lamp-ballast system with a specific ballast factor will allow a designer to better minimize energy use by "tuning" the lighting levels in a space. For example, in new construction, high ballast factors are generally best, since fewer luminaires will be required to meet the light-level requirements. In retrofit applications or in areas with less critical visual tasks, such as aisles and hallways, lower ballast factors may be more appropriate (Eley Associates, 1993).

Ballast Efficacy Factor. The ballast efficacy factor is the ratio of ballast factor (as a percentage) to power (in watts); it is expressed in lumens per watt for a given lamp–ballast combination. Comparisons using the ballast efficacy factor are valid only when comparing ballasts for equivalent systems in terms of lamp type and number of lamps.

Because ballast factor is an indication of the amount of light produced by a ballast-lamp combination, and input watts an indication of power consumed, ballast efficacy factor is an expression of lumens per watt for a given lighting system. This measurement is generally used to compare the efficiency of various lighting systems. For example, a ballast with a ballast factor of 0.88 using 60 watts of input power has a ballast efficacy factor of 1.466 ($0.88 \times 100 / 60 = 1.466$). A different ballast utilizing the same input power with a ballast factor of 0.82 has a ballast efficacy factor of 1.366. The first ballast therefore offers greater efficiency because it has a higher ballast efficacy factor (1.466 vs. 1.366).

Power Factor. The power factor of a ballast is a measure of how effectively a ballast converts the voltage and current supplied by a power source into watts of usable power delivered to the lamp. In general, the power factor is determined from the ballast design and is considered high (if above 0.90), low (below 0.79), or "corrected" (0.80 to 0.90). The power factor addresses the effective use of power supplied to a ballast—it does not relate to the luminous output of a ballast-lamp combination. High-power-factor ballasts are more expensive, but the additional cost is readily repaid by lower line losses, smaller circuit conductors in long runs, and a larger number of fixtures per circuit. Energy conservation and economic considerations dictate the use of power-factor-corrected or high-power-factor ballasts.

(b) Ballast Types

There are three basic types of ballasts: magnetic, hybrid, and electronic. Ballast technology has greatly improved over the past years because of energy policy changes developed by the U.S. DOE, state energy offices, the ACEEE, the Alliance to Save Energy, the Natural Resources Defense Council, and lighting manufacturers.

Magnetic. Magnetic ballasts (core-and-coil) contain a magnetic core of several laminated steel plates wrapped with copper windings; they operate at line frequency (60 Hz). These ballasts (Fig. 14.8) have become essentially obsolete, although they are found in existing buildings.

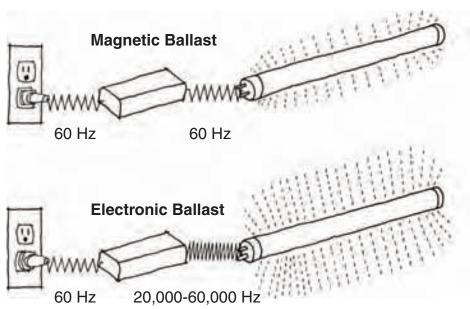


Fig. 14.8 *Ballasts for fluorescent lamps have traditionally been of the electromagnetic type, operating at a frequency of 60 Hz. Electronic ballasts operate at frequencies of 20,000–60,000 Hz and cause lighting systems to convert electric power to light more efficiently than systems run by electromagnetic ballasts. (Drawing by Jonathan Meendering; © Alison Kwok; all rights reserved.)*

Hybrid. Also called cathode-disconnect ballasts, hybrid ballasts use a magnetic core-and-coil transformer and an electronic switch for the electrode-heating unit. Like magnetic ballasts, they operate at 60 Hz. The ballast disconnects the electrode-heating unit after starting the lamp.

Electronic. Solid-state electronic ballasts operate lamps at 20–60 kHz and have less power loss than magnetic ballasts. Lamp efficacy increases by approximately 10–15% compared to operation at 60 Hz. Electronic ballasts are lighter, are more energy-efficient, generate less heat, and are virtually silent. They are also available as dimming ballasts, which allow light output to be controlled between 1% and 100%.

Special. Lamps operating at other than 430 mA, including low-current and high-current units, require matching ballasts to supply the required current, waveform, and circuitry. Use of one manufacturer's low-current lamp with another's low-current ballast is not suggested without prior testing or a specific manufacturer's recommendation. The principal varieties of special ballasts are as follows:

1. *Low-current ballasts* are intended to match specific low-current lamps, including T8 triphosphor units, slimline lamps, and others.
2. *High-current ballasts* are intended to be used with high-output lamps. The purpose of this combination is either to increase output in an existing installation or to reduce the number of fixtures in a new installation.
3. *Energy-saving ballasts* are designed to reduce the total wattage of the lamp–ballast combination. Part of this power reduction is produced by more efficient design of the ballast itself. Another part is due to a lower current rating for the lower wattage of the lamp itself. A third portion is frequently a switching arrangement in the ballast that disconnects the lamp filaments after an arc is struck (after the lamp ignites). This technique can save 4 to 8 W per lamp–ballast pair.
4. *Multilevel ballasts* are useful when it is desired to change lighting levels evenly. The usual unit is two-level—that is, full output and 50%—but three-level units are available for full, two-thirds, and one-third output.

In addition to these ballast types, there are special units for low or high ambient temperature, weatherproof units, and low leakage-to-ground units for hospital applications.

(c) Ballast Performance

Heat. Ballast heat is usually transferred to the luminaire body by direct metal-to-metal contact (which must be unimpeded) and is then dissipated by radiation and convection from the fixture. The location and method of fixture installation affect the heat transfer from the fixture and, consequently, the ballast temperature. Operating temperature directly affects ballast life. At normal operating temperature, a ballast life of 12 to 15 years can be expected. Generally, ballast life is halved for every 50F° (27.8C°) above the standard 194°F (90°C) operating temperature, and, conversely, is doubled for every 50F° (27.8C°) reduction in operating temperature below 194°F (90°C). Electronic ballasts will usually start a lamp at 50°F (24°C) minimum. A special ballast is required for starting at temperatures down to 0°F (−18°C). The more efficient (and thus cooler) operation of electronic ballasts reduces air-conditioning costs. Not only do the ballasts operate cooler, but lamps operated by electronic ballasts produce the same light output with lower losses. Therefore, overall energy costs for an electronic ballast installation are reduced because the fixtures use less energy and produce less heat for the same light output.

Noise. All electromagnetic and some electronic ballasts make a humming sound that originates from the inherent magnetic action causing vibrations in the steel laminations of the core-and-coil assembly. Because electronic ballasts have a small (or no) core-and-coil assembly, they have the lowest noise output. Most electronic ballasts make almost no sound. Ballast noise, if any, may be amplified by (1) the method of mounting the ballast in the fixture, (2) loose parts in the fixture, or (3) ceilings, walls, floors, and hard furniture that reflect the noise. Ballasts are sound-rated by a letter, A through F, which indicates not actual sound produced, but performance in a space—a rating of A designating the quietest ballast. Selection should be made on the basis of the ballast sound rating and the requirements of the installation.

Flicker. Flicker is caused by extinguishment and reignition of the arc within a fluorescent tube and is visible only when a lamp is operated at a relatively low frequency (such as the 60 Hz typical of North American electrical systems) and where long-persistence phosphors are thin or entirely absent (at the extreme ends of a lamp, for example). A magnetic ballast does not alter the incoming line frequency. Thus, the lamp voltage crosses zero 120 times each second, resulting in 120 light-output oscillations per second. Flicker is typically not noticeable to most viewers—but there is evidence that flicker of this magnitude can cause adverse effects, such as eyestrain and headache. Most electronic ballasts operate at higher-than-line frequency, which reduces lamp flicker to an essentially imperceptible level. Manufacturers can specify the flicker percentage of a particular ballast working in conjunction with a given lamp type and phosphor composition. For a standard phosphor lamp operated at 60 Hz (magnetic ballast), the flicker percentage is about 30%; with an electronic ballast (high frequency), the flicker percentage is nil.

Dimming Control. Dimming of electronically ballasted lamps is accomplished within the ballast itself. The dimming process uses energy that should be accounted for in lighting system energy-use calculations. Electronic ballasts alter the power input to the lamps through a low-voltage signal into the ballast output circuit. High-power switching devices to condition the input power are not required. This arrangement allows control of one or more ballasts independent of the electrical distribution system.

Radio Noise. Occasionally, a defective ballast will cause radio noise—commonly referred to as radio frequency interference (RFI). In general, however, RFI is not produced by a ballast, but by the arc discharge in a fluorescent tube. To minimize RFI, ballasts are available with integral RF noise suppressors. In extreme cases, additional suppression can be obtained by installation of RF noise attenuators in a lighting fixture.

Fluorescent Lamps

The fluorescent lamp is the best-known and most widely used type of gaseous discharge lamp. Since their introduction in 1937, fluorescent lamps have almost completely supplanted incandescent lamps in all fields except display, residential, and specialty lighting. The typical linear fluorescent lamp comprises a cylindrical glass tube sealed at both ends and containing a mixture of an inert gas, generally argon, and *low-pressure* mercury vapor. Built into each end of the tube is a cathode that supplies the electrons to start and maintain an electric arc, or gaseous discharge. Short-wave UV radiation, which is produced by the mercury vapor, is absorbed by phosphors coating the inside of the tube, causing a reaction that emits visible radiation (light). The particular mixture of phosphors used governs the quantity and spectral quality of the light output. Light from fluorescent sources radiates from a larger lamp surface area than is the case with incandescent sources. The light is diffuse, which is suitable for illuminating or washing large areas such as ceiling planes.

14.6 FLUORESCENT LAMP CONSTRUCTION

Rapid-start and instant-start fluorescent lamps (having made preheat lamps obsolete) are commonly used today. Lamp families include linear and compact. Linear lamps are tubular in shape, with the most popular versions being T8 and T5 (26-mm and 16-mm) in standard and high output (HO) and the legacy T12 (38-mm) lamp. Compact fluorescents include dedicated socket versions of single-tube, double-tube, and triple-tube lamps. The descriptions that follow cover *standard* lamps and circuits. Special lamps, accessories, and circuits, including low-wattage lamps, triphosphor lamps, and special-shape lamps, are discussed separately.

(a) Preheat Lamps

Older fluorescent fixtures use a preheat technology that heats the fill gas in order to start the lamp; they use a mechanism called a *starter*. Preheat fixtures either have an automatic starter or require a manual starting action. The original T12 (38-mm) fluorescent lamp was a preheat design. Construction of a typical hot cathode lamp (used with both preheat and rapid-start types) is shown in Fig. 14.9. All preheat lamps have bi-pin bases.

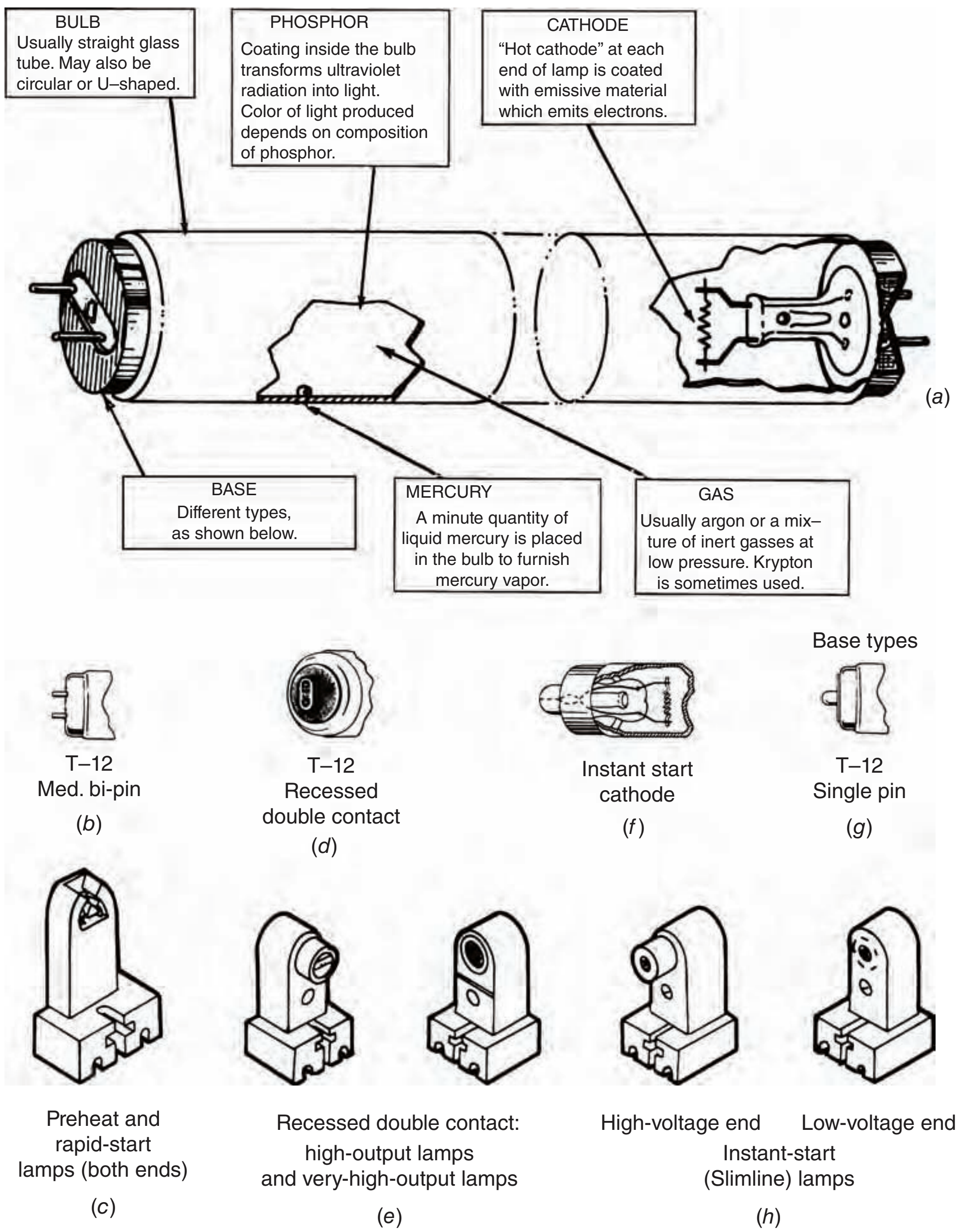


Fig. 14.9 *Details of typical fluorescent lamps and associated lampholders. (a) Construction of preheat-rapid-start bi-pin base lamp. (Courtesy of GTE/Sylvania, Inc.) This type of lamp has type (b) base and is held in type (c) lampholder. High-output (HO) and very-high-output (VHO) rapid-start lamps use a recessed double-contact (dc) base (d) and lampholders (e). Instant-start lamps are similar in construction to (a) except with cathode construction (f), have a single-pin base (g), and use single-pin lampholders (h), which are different at each end.*

This lamp circuit utilizes a separate starter, a small cylindrical device that plugs into a preheat fixture. When the lamp circuit is closed, the starter energizes the cathodes; after a 2- to 5-second delay, it initiates a high-voltage arc across the lamp, causing it to start. Most starters are automatic, although in desk lamps, preheating is accomplished by depressing a start button for a few seconds, and then releasing it. This closes the circuit and allows the heating current to flow; releasing the button causes the arc to strike. Preheat lamps are no longer the industry standard but are included here as a point of comparison.

(b) Rapid-Start Lamps

Today, the most popular fluorescent lamp design is the rapid-start lamp, shown in Fig. 14.10. This design functions similarly to the traditional preheat lamp, but without a starter switch. Instead, the lamp's ballast constantly channels current through both electrodes, eliminating the delay inherent in a preheat circuit. This current flow is configured so that there is a charge difference between the two electrodes, establishing a voltage across the tube. Most fluorescent fixtures with two or more lamps are known as *rapid start*. When the lamp circuit is energized, the arc is struck immediately. No external starter is required. Because of the similarity of operation, rapid-start lamps will operate satisfactorily in a preheat circuit. The reverse is not true, because a preheat lamp requires more current to heat the cathode than the rapid-start ballast provides.

Most rapid-start T12 lamps operate at 430 mA. If the current is increased, the output of the lamp also increases. Two generic types of higher-output rapid-start lamps are available. One operates at 800 mA and is called simply *high-output* (HO). The second, operating at 1500 mA (1.5 A), is called (by different manufacturers) *very-high-output* (VHO), *super-high-output*, or simply the *1500-mA, rapid-start lamp*. There is also a 1500-mA lamp that uses what looks like a dented or grooved glass tube. This lamp has a somewhat higher output than a standard VHO tube. All HO lamps use double-contact bases (see Fig. 14.9) and special ballasts. HO lamps are used in applications such as outdoor sign lighting, street lighting, and merchandise displays where high output is required from a limited-size source. Because of the serious heat problems involved, VHO lamps are frequently operated without enclosing fixtures. Conversely, HO and VHO lamps are frequently used in cold environments that would prevent proper operation of a standard output 430-mA lamp. Most HO and VHO lamps have slightly lower luminous efficacy than a standard 430-mA, rapid-start lamp and have a considerably shorter life. It should be noted that only rapid-start lamps are to be used with motion sensors or in conjunction with sequential repetitive dimming of lamps. Use of instant-start lamps in this application will overload the cathodes, and lamp life will be reduced.

(c) Instant-Start Fluorescent Lamps

Instant-start fluorescent lamps use a high-voltage transformer to apply a very high initial voltage to the cathodes. An excess of electrons on the cathode surface forces some electrons into the fill gas, which ionizes the gas. This creates an instant voltage difference between the cathodes, establishing

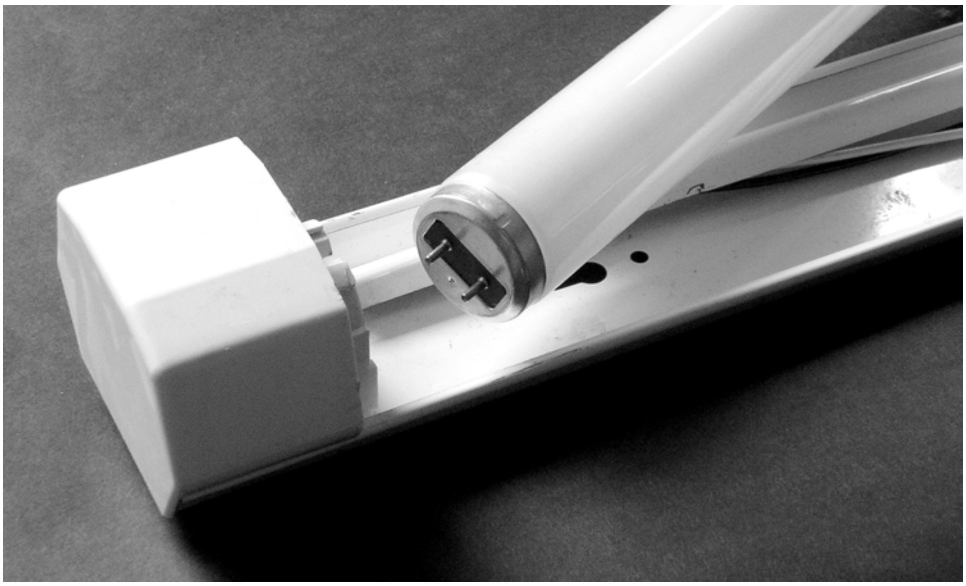


Fig. 14.10 *Rapid-start fluorescent lamps have two pins that slide against two contact points in an electrical circuit. The ballast constantly channels current through both electrodes, creating a charge difference between the two electrodes and establishing a voltage across the tube. (Photo by Jonathan Meendering; © Alison Kwok; all rights reserved.)*

an electric arc. These lamps have only a single pin at each end that also acts as a switch to break the ballast circuit when the lamp is removed, thus lessening the shock hazard (see Fig. 14.9). The lamps are generally operated in two-lamp circuits at various currents; normal currents are 200 and 430 mA. The high-voltage starting characteristic of instant-start circuits lowers the lamp life to about half that of a corresponding rapid-start lamp. Instant-starts have the advantage of being able to start at much lower ambient temperatures (below 50°F [10°C]) than rapid-start circuits. This starting characteristic makes the instant-start lamp and circuit particularly applicable to outdoor use.

14.7 FLUORESCENT LAMP LABELS

Standard fluorescent lamp labels are printed on the end of a lamp and use several identifying letters and numbers, as shown in Table 14.3. The typical labeling is in the form FSWWCCC-TDD (each manufacturer has variations on this format). Depending upon the type of fluorescent lamp, designations for color rendering index and color temperatures are also included on the label.

TABLE 14.3 Fluorescent Lamp Label Designations

Label	Explanation
F	Fluorescent lamp. "G" means germicidal shortwave UV lamp.
S	Style—no letter indicates a normal straight tube; "C" means Circline.
W	Nominal power in watts: 4, 5, 8, 12, 15, 20, 30, 40, etc.
CCC	Color. W = white, CW = cool white, WW = warm white, BL/BLB = black light, etc.
T	Tubular bulb
DD	Diameter of tube in eighths of an inch. T8 is 1 in. (nominal 25 mm), T5 is $\frac{5}{8}$ in. (nominal 15 mm), etc.

14.8 FLUORESCENT LAMP TYPES

(a) T8 Fluorescent Lamps

Over the past 20 years, T8 lamps have afforded designers (and their clients) cost-effective and energy-efficient lighting systems that are visually comfortable and have a high degree of flexibility in their application. T8 lamps are 1 in. (25 mm) in diameter; they are available in wattages of 17, 25, 32, and 40 W at 2-ft, 3-ft, 4-ft, and 5-ft (600-mm, 900-mm, 1200-mm, and 1500-mm) lengths, respectively. There are two color rendering categories of T8 lamps: 700 (75 CRI) and 800 (85 CRI) series, which relate to the color rendering properties of the triphosphor coatings used. Lamp manufacturers have developed a standard designation to indicate the color temperature of a lamp. For example, "30" indicates a 3000 K lamp. T8 lamps are available in 3000 K, 3500 K, and 4100 K color temperatures, designated "30," "35," and "41," respectively. Table 14.4 shows a comparison of lamp technologies as fluorescent lamp manufacturers have increased efficacy and color rendering while decreasing diameter and wattage.

(b) T5 Fluorescent Lamps

T5 lamp technology was developed in Europe and introduced to North America in 1996. Although

TABLE 14.4 Comparative Characteristics of Tubular Fluorescent Lamps[a]

	T12	T8	T5	T5HO
Initial rated light output	3350 lumens	2950 lumens	2900 lumens	5000 lumens
Nominal lamp watts	40W	32 W	28W	54W
Initial lamp efficacy[1]	84 lm/W	92 lm/W	104 lm/W	93 lm/W
Initial system efficacy[2]	80 lm/W	90 lm/W	89 lm/W	85 lm/W
Lumen maintenance[1]	78%	93%	97%	95%
Maintained system efficacy	69 lm/W	84 lm/W	86 lm/W	81 lm/W
Rated life[3]	20,000 hr	20,000 hr	16,000 hr	16,000 hr
CRI	80	85	85	85
Optimum operating temperature	77°F [25°C]	77°F [25°C]	95°F [35°C]	95°F [35°C]

[a]Figures are representative; for exact figures, consult current catalogs.

[1]Based on 4-ft (1200 mm) nominal length, CRI 85 lamps.

[2]Based on 4-ft (1200 mm) nominal length, CRI 85, two-lamp rapid-start, electronic ballast.

[3]Varies with manufacturer and phosphor coating technology.

it was still expensive, the introduction of a T5 HO line in 1998 offered about twice the lumen output in the same length as its T8 counterpart, with an efficacy that is attractive in meeting project energy goals. The T5 is the first "metric" lamp introduced in the United States, yet it is commonly called T5 because of industry nomenclature. Standard and HO T5 lamps are available in 22-in., 34-in., 46-in., and 58-in. (560-mm, 864-mm, 1163-mm, and 1473-mm) lengths. The standard T5 and the T5 HO lamps are the same diameter and width. The 46-in. T5 (nominal 4 ft) is rated at 2900 lumens, similar to the lumen per watt output of a T8 lamp (2950 lumens). By contrast, the 46-in. T5 HO lamp is rated as high as 5000 lumens, offering twice the maintained light output of a T8 lamp. Because of its smaller ⅝-in. (15-mm) diameter construction, significantly less glass, mercury, and high-quality phosphors are needed for its construction. T5 lamps also allow a designer to use fewer lamps (and fixtures), thus providing certain savings on installation and long-term maintenance. The narrow lamp diameter has provided an opportunity for the design of new fixtures and for use in low-profile, indirect luminaires. The color rendering quality of light from T5 lamps (CRI 85) is excellent, although the potential for glare problems exists, which can be addressed by sophisticated shielding techniques. Utilizing T5 (and particularly T5 HO) lamps in direct-delivery lighting installations requires special attention to glare control.

14.9 CHARACTERISTICS OF FLUORESCENT LAMP OPERATION

Five characteristics define the operation of a fluorescent lamp:

- Efficacy: Light output per unit of power input
- Lumen maintenance: The decreasing output of light as a lamp ages
- Lamp life: Average (statistically defined) lamp life expectancy
- Temperature and humidity: How a lamp responds to environmental operating conditions
- Dimming: Controlling light production of the lamp

(a) Efficacy

$$\text{luminous efficacy} = \frac{\text{lumens (light output)}}{\text{watts (power consumed including ballast losses)}} = \text{lumens per watt (lm/W)}$$

The design efficacy (lumens per watt) of a fluorescent lamp depends upon the operating current and the phosphors utilized. Fluorescent lamp efficacy is further dependent upon the lamp length, ambient temperature, frequency of the electricity supply, and ballast operation. *Wattage*, in itself, is a meaningless quantity unless it is associated with a lumen output figure. Thus, energy-saving low-wattage or high-output lamps with their special ballasts are seldom the indicated choice in new design because their efficacy does not usually justify the cost premium. These special lamps are useful in retrofit work, in which case field measurements of illuminance and lamp temperature are required before selecting a replacement lamp–ballast combination.

(b) Lumen Maintenance

The lumen output of a fluorescent tube decreases rapidly during the first 100 hours of burning, and thereafter much more slowly. Phosphors deteriorate, typically blackening the ends of a lamp, thereby blocking some light. Most product catalogs list "initial lumens," which is the lamp output under *laboratory conditions* after 100 hours of burning, and "mean" or "design" lumens, which is lamp output at 40% of rated life. Unless otherwise controlled, illuminance gradually drops as a system ages until, somewhere in the middle of the effective life of the lamps (Fig. 14.11), the intended "maintained" illuminance of a system is (temporarily) achieved.

(c) Lamp Life

The life of a standard fluorescent lamp is defined as the length of time an average lamp is expected to last. This value is dependent upon the burning hours per start. Life is expressed as "rated average life" in hours of operation. The life values listed in lamp catalogs are based upon a burning cycle of 3 hours per start (with 20 minutes of "off" status) and represent the average life of a group of lamps; that is, half of the lamps in any group will have burned out at that time. Typical lamp mortality curves

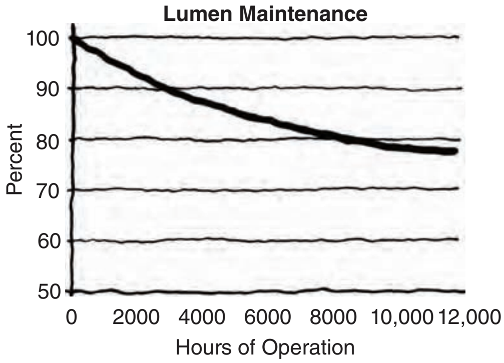


Fig. 14.11 *Generic lumen maintenance curve for fluorescent lamps; curve shows reduction in light output over time. Greater lumen maintenance means that a lamp will retain performance longer. The opposite of lumen maintenance is lumen depreciation, which represents the reduction of lumen output over time. (Drawing by Jonathan Meendering.)*

are shown in Fig. 14.12, and the effect of burning hours per start is shown in Fig. 14.13. Average rated lamp life is not the same as the time at which lamps are typically replaced, which is usually well before 50% failures occur in a batch. Several factors affect fluorescent lamp life. Longer burning hours per start will extend lamp life. Lamp life is shortened by improper lamp current, improper voltage to the ballast, or improper cathode heating.

From an energy utilization viewpoint, if a lighted space is not utilized for 10 minutes or more, fluorescent lamps should be shut off. This takes into account both direct energy consumption and the resource energy required to replace a lamp as a result of shortening its life. From a cost viewpoint, the break-even point depends upon these factors: (1) lamp life reduction as a function of burning hours per cycle, (2) cost of energy, (3) cost of lamp and lamp replacement, (4) amount of time the lamp remains off when shut off, (5) cost of switching equipment (if any), and (6) life of the building.

With this number of variables, it is not possible to give general solutions, and an individual analysis is required. Several analyses for ordinary office conditions (using lamp life data as given in Fig. 14.13: a 20-year fixture life, \$0.085/kWh energy cost, escalating 3% annually, \$1.25 lamp cost, 15-minute relamping time, and \$8 per lamp to provide the necessary switch [one switch per two 2-lamp fixtures]), have shown that lamps should be switched off any time they are not in use for 5 to 8 minutes or more. The range is caused primarily by variation in local labor rates. It is thus clearly an economic fallacy to leave lamps burning to save money.

(d) Effect of Temperature and Humidity

Fluorescent lamps are affected by extremes in ambient temperature and by high humidity. Outside of the optimal operating temperature range, 41–77°F (5–25°C), there is a rapid drop in light output and difficulty in starting. High humidity causes electrical leakage along the lamp surface, lowering the starting voltage provided by the ballast. Lamps

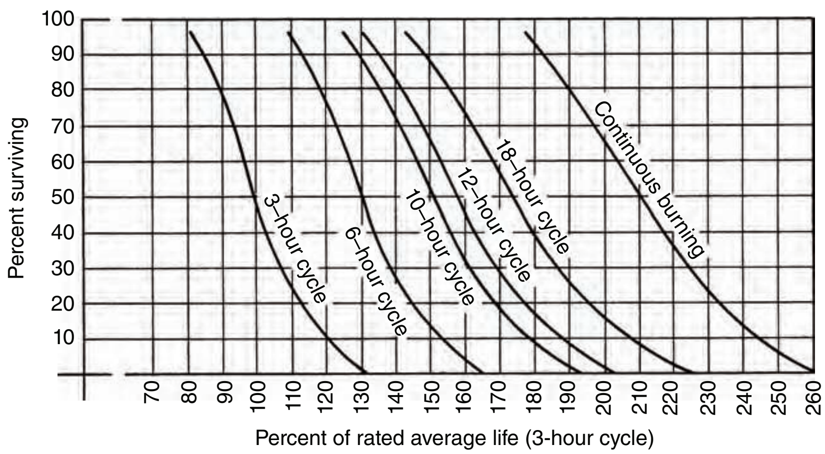


Fig. 14.12 *Typical mortality curves of standard fluorescent lamps.*

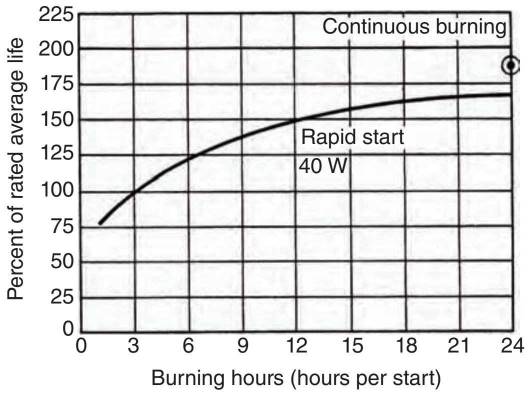


Fig. 14.13 *Effect of burning hours on fluorescent lamp life. Note that at 3 burning hours per start, the average lamp life is 100% of the nominal catalog value.*

are pre-coated with silicone to break up moisture films and prevent such leakage.

The temperature of the coolest point on the wall of the lamp bulb determines a lamp's mercury-vapor pressure, which in turn determines the lamp lumen output, wattage, and color. Maximum output for standard lamps occurs at a *bulb* temperature of 104°F (40°C). The bulb wall temperature itself is affected by room ambient temperature, airflow over the lamp (as with air-return fixtures), and the temperature of adjacent surfaces such as a ballast enclosure. Thus, catalog data on lamp output and wattage, based upon laboratory tests of bare tubes at 77°F (25°C) ambient temperature in still air, may be very far from actual field performance.

(e) Dimming

Dimming of a fluorescent lamp system can reduce energy consumption, correct overlighting, balance illuminance through integration with daylighting, and allow flexibility when full lighting output is required. Unlike incandescent lamps, which can be dimmed with just a wall-mounted device, fluorescent lamps require dimming ballasts. The dimming range differs greatly among ballasts. With most electronic dimming ballasts, output can vary between full and a minimum of about 10% of full output. However, electronic, full-range dimming ballasts are also available for some lamp types that operate lamps down to 1% of full lumen output.

A ballast can be configured so that it (1) receives a signal from a control device and subsequently (2) changes the current flowing through a lamp, thereby achieving a gradual, controlled reduction in lamp output. The characteristics of the ballast circuitry affect the duration and extent of the change in current and subsequent lamp output.

Electronic dimming ballasts for fluorescent lamps are designed to respond to either an analog or digital signal to achieve the dimming effect. Because a dimming ballast must be able to communicate with connected controllers, the method becomes the basis for a protocol (common operating parameters adopted by all manufacturers of dimming ballasts and controllers that use that method). This ensures interchangeability between a ballast made by a particular manufacturer and various controllers made by controls manufacturers. Typical applications for dimming include both new construction and retrofit installations: auditoriums and training areas, conference rooms and boardrooms, department and specialty stores, education and health-care institutions, hotels, houses of worship, private and executive offices, and restaurants.

The primary dimming methods are:

- Analog: An analog electronic dimming ballast includes components that perform these functions: electromagnetic interference filtering, rectification, power factor correction, and ballast output to power a lamp. There are several analog methods, including 0-10VDC, two-wire phase-control, three-wire phase-control, and wireless infrared, with 0-10VDC being most often used.
- Digital: The digital electronic dimming ballast includes components that perform these functions: electromagnetic interference filtering, rectification, power factor correction, ballast output to power a lamp, and control (as a micro-controller). The micro-controller functions as a storer, receiver, and sender of digital information. The micro-controller can store the ballast address, receive control signals, and send status information.
- Wireless infrared: This method uses an infrared transmitter to control the signal and does not require additional wires. The dimmer is either contained in the ballast or provided as an additional component in the light fixture. Wireless infrared control is a good retrofit solution and allows for occupant fixture control. Wireless infrared control is ideally suited for spaces where individual control is desired without additional wiring, such as conference rooms, boardrooms, and open and private offices.

14.10 FEDERAL STANDARDS FOR FLUORESCENT LAMPS

A series of U.S. legislative acts have mandated minimum standards for lamps in terms of efficacy (lumens per watt) and color rendering index (CRI). Cascading standards eliminated the manufacture and distribution of several major fluorescent lamp types with low luminous efficacies. The major lamps eliminated are 40 W F40T12 (CW and WW), 75 W F96T12 (CW and WW), and 110 W F96T12/HO (CW and WW). Lamps with very good CRI and special-service fluorescent lamps are excluded from the legislative bans.

14.11 SPECIAL FLUORESCENT LAMPS

(a) Low-Energy Lamps

The need for energy efficiency, the discontinuance of certain lamp types due to legislation, and a desire to reduce lighting levels in existing overlighted spaces, have resulted in the development of a range of low-energy lamps. Wattage ratings for these lamps are lower than those of standard lamps because they are intended primarily as lower-energy direct replacements for existing lamps. All such lamps are clearly marked by the manufacturer. They require special matching ballasts for maximum effectiveness and have an efficacy equal to, or somewhat higher than, that of standard lamps and ballasts. They have the disadvantages of higher cost, the need for special ballasts where maximum energy reduction is desired, generally shorter life, inability to be used in most dimming circuits, and problems with inventory and proper lamp replacement. Their use is appropriate only where other light-output and wattage-reduction schemes, such as circuit dimming or reduced-wattage ballasts, are inapplicable.

(b) U-Shaped Lamps

U-shaped lamps were developed to answer a need for a high-efficacy fluorescent source that could be utilized in a square fixture. The U lamp is basically a standard fluorescent tube bent into a U shape and available with 3⅝- or 6-in. (92- or 152-mm) leg spacing; three of these can be accommodated within a 2-ft × 2-ft (610 mm square) fixture. (The narrower T8 envelope of triphosphor lamps permits a tighter bend; these U lamps have a 1⅝-in. [41-mm] leg-to-leg spacing.) U lamps operate on standard ballasts and have slightly lower output than a corresponding straight tube. In all other respects, a U lamp has the same characteristics as a straight lamp of similar type.

(c) Ecologically Friendly Lamps

ALTO® lamps were developed in 1995 by the Philips Lighting Company to support a reduction of mercury at the source and provide users with environmentally responsible methods for disposal. The ALTO family of lamps includes a broad selection of TCLP-compliant lamps: linear and compact fluorescents, high-pressure sodium lamps, metal–halide, U-bent fluorescents, and the lead-free MasterLine™ ALTO lamps, all of which can be recycled (always the preferred method) or disposed of conventionally. TCLP is the *Toxicity Characteristic Leaching Procedure*—a test developed by the EPA to measure hazardous substances that might dissolve into the ecosystem; the test is used by the federal government and by most states to determine whether old fluorescent lamps should be characterized as hazardous waste. All fluorescent lamps contain mercury; however, ALTO lamps have the lowest mercury doses available (on average, 70% less mercury than the 2001 industry average) on the market. This product development encouraged other manufacturers to reduce the mercury content in their products—as in the Osram Sylvania Ecological® and General Electric Ecolux® lines.

(d) UV Lamps

UV lamps emit radiation in the UV spectrum, which includes all electromagnetic radiation with wavelengths in the range of 10–400 nanometers (nm).

- The UVA range includes wavelengths from 315 to 400 nm. Wavelengths from about 345 to 400 nm are used for "black light" effects (causing many fluorescent objects to glow). The UVA wavelengths border the visible spectrum, and the lamps are usually slightly visible if isolated from conventional lamps. Shorter UVA wavelengths from 315 to 345 nm are used for sunning.

- UVB refers to wavelengths from 280 to 315 nm. These wavelengths are more hazardous than UVA wavelengths and are largely responsible for sunburn.
- UVC refers to shorter UV wavelengths, usually from 200 to 280 nm. Wavelengths in this range, especially from the low 200s to about 275 nm, are especially damaging to exposed biological cells. Such short-wave UV radiation is often used for germicidal purposes (either in industry or for indoor air quality mitigation).

Although UV lamps are not commonly used in architectural lighting, they are included in this section as specialty lamps because they address a wide range of applications in industrial, technological, laboratory, and medical settings. UV lamps include fluorescent black lights, fluorescent tanning and medical UV lamps, "RS" reflector ("floodlamp") sunlamps, and germicidal and EPROM (erasable programmable read-only memory) erasing lamps.

14.12 COMPACT FLUORESCENT LAMPS

Compact fluorescent lamps (CFLs) offer a comparable (in brightness and color rendition), energy-efficient alternative to incandescent lamps. Unlike standard fluorescent lamps, they can directly replace standard incandescent bulbs.

CFLs are simply folded fluorescent tubes with both ends terminating in a common base. Some compact fluorescent lamps have the tubes and ballast permanently connected with a screw-in medium base. Others have separate tubes and ballasts, allowing the tubes to be replaced without changing the ballast. As a result, an exhausted lamp is simply replaced in the existing ballast, resulting in considerable economy. A CFL produces a diffuse light, unlike single-point incandescent lamps. This is an important factor to consider when replacing incandescent lamps with CFLs in high-ceiling applications.

CFLs are manufactured in a variety of styles or shapes: two, four, or six tubes; circular or spiral tubes (Fig. 14.14). They are efficient at lower wattages and can produce light output equivalent to

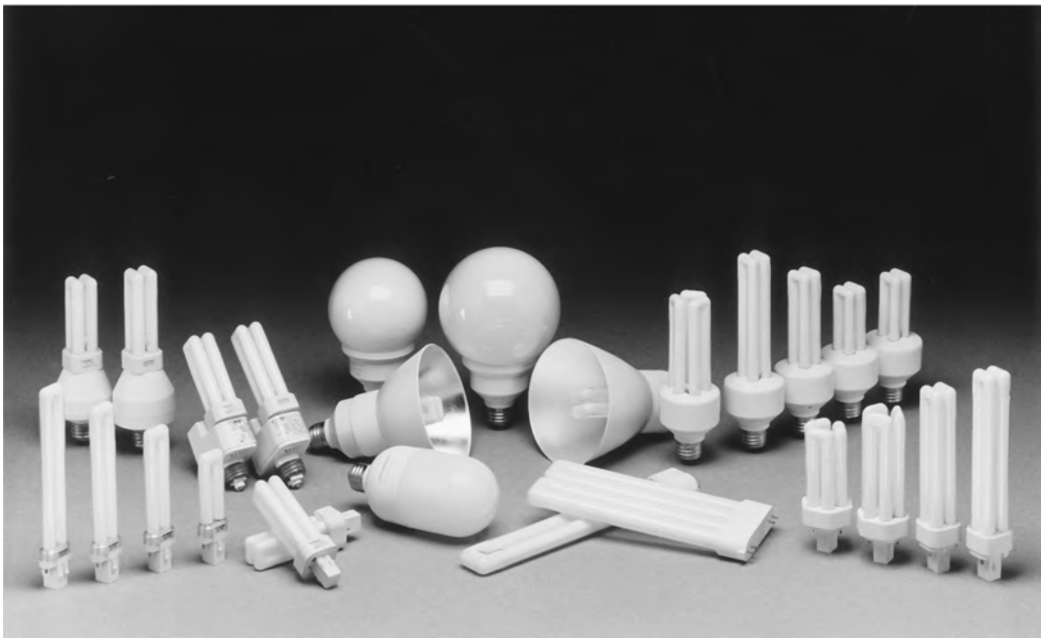


Fig. 14.14 *Family portrait of compact fluorescent lamp designs. Pin-base lamps designed for use with a separable ballast are shown in the foreground, the same lamps mounted in their screw-base ballasts are in the left background, and the one-piece combined lamp–ballast design stands in the right background. Globe and reflector-type replacements for incandescent lamps are in the center of the photo. (Courtesy of Osram-Sylvania.)*

TABLE 14.5 Equivalent Wattage of Common Incandescent Lamps and Compact Fluorescents

Incandescent Watts	Compact Fluorescent Watts
50	9
60	15
75	20
100	25
120	28
150	39

Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy (http://apps1.eere.energy.gov/consumer/your_home/lighting_daylighting/index.cfm/mytopic=12060)

TABLE 14.6 Cost Comparison for Operation of an Incandescent Lamp and a Compact Fluorescent Lamp

	Incandescent 100 W 1750 lumens	Compact Fluorescent 27 W 1750 lumens
Lamp cost ($)	$0.50	$20.00
Rated life (hours)	750	10,000
Efficacy (lumens per watt)	17	64
Energy cost (@8¢/kwh for 10,000 hrs)	$80	$22
Total cost (lamps + energy)	$85	$42

Sources: U.S. Department of Energy, Energy Efficiency and Renewable Energy (http://apps1.eere.energy.gov/consumer/your_home/lighting_daylighting/index.cfm/mytopic=12060) and Southface Energy Institute (http://www.southface.org/web/resources&services/publications/factsheets/13e_lite.pdf)

that of higher-wattage incandescents (e.g., a typical 60-W incandescent lamp with a 900-lumen output could be replaced by a 15- to 19-W CFL). The total surface area of the tube(s) determines how much light is produced. The efficacy of lamp–ballast combinations ranges from 55 to 75 lm/W, assuming an electronic ballast. Lamps with magnetic ballasts are available but are not favored because of excessive heat, weight, and flicker, and reduced efficiency. Lamp colors are similar to those of straight lamps (i.e., 3000 K, 3500 K, 4200 K, and 5000 K). All CFLs have a CRI of 80 or higher. Their life is 10,000 to 12,000 hours based on 3 hours per start. Table 14.5 compares the wattage of commonly available incandescent lamps to that of a CFL that provides similar light output.

A major advantage of using CFLs is saving money, as shown in Table 14.6. This analysis assumes that a lamp is on for 6 hours per day and that the electric rate is 8 cents per kilowatt-hour.

High-Intensity Discharge Lamps

High-intensity discharge (HID) lamps (Fig. 14.15) produce light by discharging electricity through a high-pressure vapor. Lamps in this category include mercury-vapor (CRI range 15–55), metal–halide (CRI range 65–80), and high-pressure sodium (CRI range 22–75). These lamps are characterized by high luminous efficacy, defined warmup time, noticeable restrike time, and historically poor color rendering capabilities. Mercury-vapor lamps were the first commercially available HID lamps, and the early products produced a bluish-green light. Today they are available with a color-corrected whiter light; because of inefficiency and potential hazards, however, said lamps are being replaced by newer and more efficient metal–halide and high-pressure sodium lamps. Standard high-pressure sodium lamps have the highest efficacy of all HID lamps, but they produce a yellowish light. High-pressure sodium lamps that produce a whiter light are now available, but their luminous efficacy is somewhat lower.

HID lamps are typically used when high illuminance is required over large areas, and when energy efficiency and/or long life are desired. Typical applications include gymnasiums, large public areas, warehouses, outdoor activity areas, roadways, parking lots, and pathways.

14.13 MERCURY-VAPOR LAMPS

The mercury-vapor lamp was the first HID lamp to be developed, and for many years it was the only commercially available HID lamp. It has largely been supplanted by the metal–halide lamp because of the latter's better color rendering and luminous efficacy. Although many installations with mercury-vapor lamps exist, this technology is no longer specified for new buildings. For the same energy efficiency, metal–halide lamps have better color rendering properties and are often preferred for

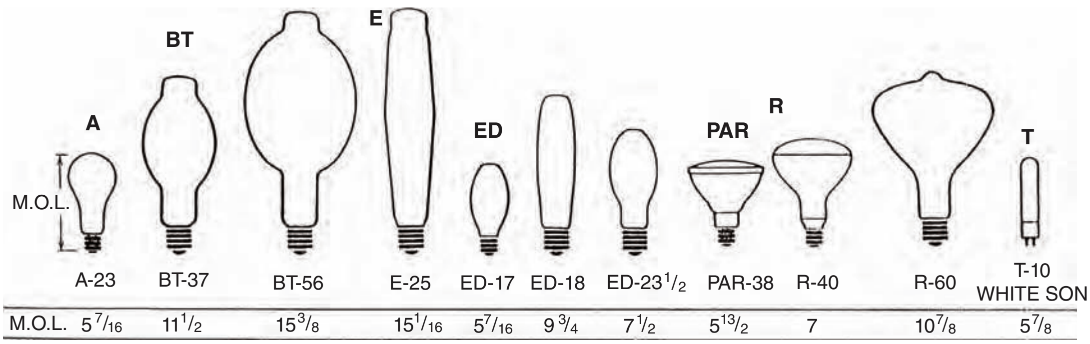


Fig. 14.15 *Bulb shapes for most HID lamps, with their maximum overall length (M.O.L.).*

indoor applications. Mercury-vapor lamps, most often used to light streets, gymnasiums, and sports arenas, must be maintained properly to be safe.

A mercury-vapor lamp operates by passing an electric arc through *high-pressure* mercury vapor contained in a quartz arc tube (Fig. 14.16). This produces radiation in both the UV region (as in the low-pressure fluorescent lamp tube) and the visible region, principally in the blue–green band. This color mix is characteristic of a clear mercury lamp.

(a) UV Radiation

A considerable portion of a mercury vapor lamp's radiation spectrum is in the UV range. This does not normally constitute a hazard to people because the outer glass bulb (even a clear bulb) absorbs most of the UV radiation while transmitting light. If the outer bulb is broken, however, the quartz arc tube will continue to burn, and the unfiltered UV radiation becomes a safety hazard, particularly to the skin and eyes. As a result, manufacturers include a warning about this condition with all mercury lamps sold. A safety-type mercury vapor lamp is readily available that will self-extinguish if the outer glass envelope is broken. An alternative is to use mercury-vapor lamps in an enclosing fixture designed to both prevent lamp breakage from external sources, such as vandalism, and protect occupants in the (unlikely) event of a spontaneous lamp fracture. In the interest of safety, it is suggested that mercury lamps be shut off at least once a week for at least 30 minutes to allow them to cool completely.

Regarding protection from the injurious effects of UV radiation, note that:

1. The shorter the UV wavelength, the more potentially irritating it is to the skin and eyes. Germicidal UV radiation is in the short-wave range (200 to 300 nm).
2. White plaster and polished metal are good reflectors of UV radiation. As a result, UV radiation reflected from such surfaces is almost as dangerous as that from line-of-sight exposure to a UV source.

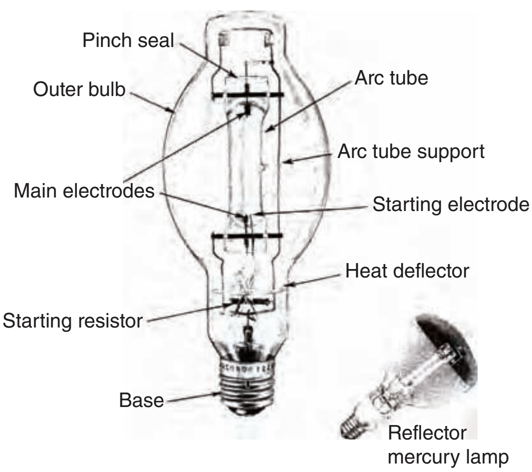


Fig. 14.16 *Construction of a typical clear mercury-vapor lamp.*

(b) Lamp Life

Mercury-vapor lamp life is extremely long, averaging 24,000 hours or more based upon 10 burning hours per start. Mercury-vapor lamps are not suitable for applications that are subject to constant switching. Their life is affected by ambient temperature, line voltage, and ballast design.

(c) Lumen Maintenance

This lamp property depends upon the specific type of lamp and its burning position. Manufacturers publish data for *each* of their lamp types. In general, clear lamps have the best lumen maintenance, followed by color-improved and phosphor-coated units.

(d) Color Correction and Efficacy

Color correction is normally required because the blue–green light from a clear mercury-vapor lamp distorts almost all object colors. (These lamps are frequently used to illuminate outdoor gardens because the blue–green light enhances the green of trees and vegetation.) Color correction is achieved by adding phosphor to the inside of the outer bulb. The phosphors convert UV radiation to light exactly as in fluorescent lamps, and the treatment of the glass acts as a filter to some of the blue–green radiation. The phosphors reradiate generally in the red band, which is entirely absent in the clear lamp color. Depending upon the arc tube design and the phosphors used, the color of the emitted light can be corrected to make it acceptable for general indoor use. Lamps are available in clear, white, color-corrected, and deluxe white, in ascending order of color improvement. Luminous efficacy, including ballast loss, ranges from 25 lm/W for a 50-W lamp to a maximum of 55 lm/W for a 1000-W color-corrected lamp. Note that, in general, efficacy is lower than for fluorescent lamps. CRI ranges from a low of 20 for a clear lamp to a high of only 50 for a deluxe white lamp. A short list of representative lamp data is given in Table 14.7.

TABLE 14.7 Typical Data for Mercury-Vapor Lamps

Watts	Type[a]	Bulb[b]	Initial Lumens	Efficacy[c] (LM/W)
100	DX	A-23	4300	39
100	DX	ED-23½	4400	40
100	DX	R-40	2800	25
250	DX	ED-28	13,000	47
250	DX/SB	E-28	6000	24
400	DX	R-57	23,000	54
450	W/SB	BT-37	9700	28
700	DX	BT-46	43,000	55
750	W/SB	R-57	14,000	19

Note: All lamps using an external ballast have a life of 24,000+ hours, based upon 10 hours burning per start. Life of self-ballasted lamps: 250 W—12,000 hours; 400 W and 700 W—16,000 hours.

All deluxe lamps with external ballast have a CRI of 45 and a CCT of 3700 K. All self-ballasted lamps have a CRI of 50 and a CCT of 3300 K.

[a]Type abbreviations: DX = deluxe; W = white; SB = self-ballasted.

[b]For bulb shape and dimensions, see Fig. 14.15.

[c]Efficacy includes an estimated loss in a magnetic ballast. For self-ballasted lamps, efficacy is as shown.

(e) Ballasts and Lamp Starting

Ballasts are required, as with all gaseous discharge lamps, to start a mercury-vapor lamp and thereafter to control the arc. From 3 to 6 minutes are required for a lamp to reach full output because heat must be generated by electron flow to vaporize the mercury in the arc tube before the arc will strike. Once extinguished (turned off), a lamp must cool before restrike is possible. This restart delay amounts to 3 to 8 minutes, depending upon the ballast type, and is an important consideration in design, as a momentary power outage will extinguish all lamps, leaving an interior area in the dark. Mercury-vapor luminaires that utilize small halogen lamps to supply light during such outages are available. Alternately, some incandescent lighting can be employed to maintain minimum illuminance.

The principal mercury-vapor ballast types are reactor, regulating, and electronic. Magnetic mercury ballasts are large, heavy, and quite noisy. Where this may be a problem, remote ballast mounting should be considered or lighter, quieter, and more expensive electronic ballasts used. Because lamp-operating characteristics depend heavily upon the type of ballast and because the choice of an appropriate ballast involves highly technical electrical considerations, selection should be left to an electrical engineer or lighting consultant.

(f) Self-Ballasted Lamps

These have been available for some years and consist of a screw-base color-corrected lamp with an internal resistive/reactive ballast. They have a CRI of 50, an efficacy of 20 to 25 lm/W, and a correlated color temperature (CCT) of 3500 K to 4000 K. Their great advantage is their long life, which can be used beneficially in applications involving: burning periods of 8 to 10 hours minimum, relative inaccessibility, limited space that precludes ballast installation, and indifferent color rendering requirements.

(g) Application

Mercury-vapor lamps are applicable to indoor and outdoor use, with proper attention to performance characteristics. The most common exterior application is for parking lots. Indoor application is generally limited to mounting heights of 10 ft (3 m) AFF (above finish floor) or higher, to avoid direct glare potential and permit adequate floor area coverage. Their use in industrial spaces and stores was once common, but today use of metal–halide lamps is typical. Warehouses and non-color-sensitive industrial areas continue to use mercury-vapor lamps.

14.14 METAL–HALIDE LAMPS

This lamp began its life in the early 1960s as a modified mercury-vapor lamp. Major advances in miniaturization, color rendering, color temperature, and consistency—by the addition of halides such as thallium, indium, and sodium to the arc tube—resulted in changes in the output, efficacy, color, and life of the lamp. Metal–halide lamps have excellent color characteristics and therefore almost unlimited applicability. Pulse-start metal–halide lamps utilize a glass arc tube to contain the arc. Pulse-start technology includes a new family of lamps (it has been used with high-pressure sodium lamps), and improves the start system, efficacy, and lumen maintenance, while also yielding shorter warmup and restrike times. The number of types and sizes is so large, and changes so rapidly, that any abbreviated tabulation would be inadequate or misleading. (Always consult a manufacturer's catalog for current and accurate lamp data.)

Ceramic metal–halide lamps were introduced to the market a number of years ago and have become an industry standard, offering a high CRI (80–90), a color temperature of 3000 K or 4100 K, improved lumen maintenance, and stable color consistency. Typical metal–halide lamp characteristics and types are discussed in the following subsections.

(a) Lamp Configurations

Construction details for a basic metal–halide lamp are shown in Fig. 14.17 and are similar to those of its "parent" mercury-vapor lamp. In addition to this design (in a BT-shaped bulb), metal–halide lamps are manufactured in elliptical bulbs, PAR reflector lamps, and single- and double-ended tubular shapes (Figs. 14.18 and 14.19).

(b) Safety

Being essentially a modified mercury-vapor lamp, a metal–halide lamp carries the same safety warning as a mercury lamp. An additional warning, however, refers to the fact that metal–halide lamp arc tubes have a tendency to explode; therefore, the lamp must be used in an approved enclosing luminaire. All major manufacturers also make lamps with internal shields that will contain the flying pieces of a ruptured arc tube without damaging the outer bulb. Such lamps may be used in open lighting fixtures. One such lamp is illustrated in Fig. 14.19.

As with mercury-vapor lamps, manufacturers also produce a line of safety metal–halide lamps that self-extinguish within 15 minutes of an outer bulb fracture, thus limiting exposure to harmful UV radiation. These safety features are clearly noted

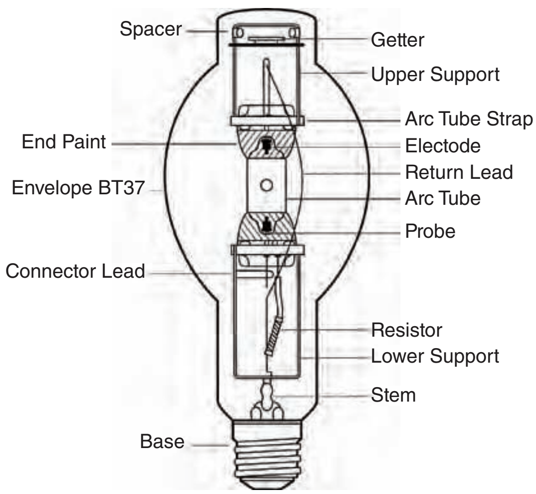


Fig. 14.17 *Construction details of a 400-W standard metal–halide lamp, which can be mounted either horizontally or vertically. (Courtesy of Osram-Sylvania.)*

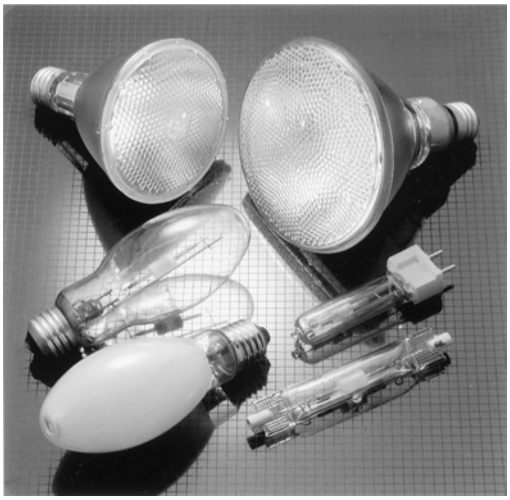


Fig. 14.18 Various configurations of metal–halide lamps. Clockwise from the bottom left: phosphor-coated and clear elliptical bulbs; PAR 30 and 38 reflector lamps; single-ended and double-ended tubular lamps—all have ceramic arc tubes and a CRI greater than 80. (Courtesy of GE Lighting.)

on the lamps by trade name and sometimes by description.

(c) Designs, Shapes, and Ratings

The metal–halide lamp designs available as of this writing are:

- Standard lamps, available in ED, BT, and PAR shapes, in wattages from 50 to 1500 W, efficacies of 75 to 105 lumens per watt with magnetic ballasts, and slightly higher with electronic ballasts (efficacy also increases with wattage).

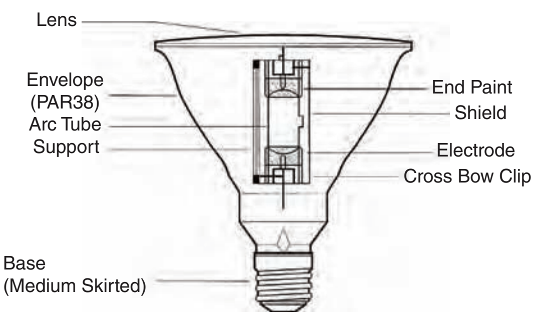


Fig. 14.19 Construction details of a PAR enclosure for a metal–halide lamp. The lamp itself is tubular and constructed with a surrounding protective shield designed to contain arc tube fragments in the event of a violent rupture. (Courtesy of Osram-Sylvania.)

  Lamps are clear or phosphor-coated, with a CCT ranging from 3000 K to 4200 K and a CRI ranging from 65 to 85. Their life, at 10 burning hours per start, varies from 10,000 to 20,000 hours depending upon lamp type, size, and burning position.
- Safety-shielded lamps with integral shields to contain a ruptured arc tube.
- Self-extinguishing lamps designed to shut down automatically upon a break in the outer glass envelope.
- High-output lamps designed for a specific burning position (as specified on each lamp). Output is 5% to 8% higher than that of standard lamps, but the color rendering is somewhat poorer, with a CRI range of 65 to 70.
- Single-ended and double-ended tubular lamps. These lamps are characterized by a very high CRI (80–93); a somewhat shorter life than standard lamps, particularly for the single-ended units (6000–10,000 hours); and slightly lower efficacy (70–85 lm/W). They are intended for applications requiring very high color rendering.

(d) Operating Characteristics

Metal–halide lamps are not instant-starting; they require approximately 2 to 3 minutes for initial startup and 8 to 10 minutes for restrike. (Tubular lamps require only about half of these times.) As a result, when they are used for indoor installations, a secondary instant-start source must be available. A number of manufacturers produce special hot-restrike ballasts that provide immediate restrike of lamps on restoration of power after an outage. Lamp output on restrike is inversely proportional to the duration of a power outage.

The spectrum of light produced by a metal–halide lamp changes as a lamp ages. The change is gradual, definite, but usually unnoticed and depends upon the particular design of lamp. Where color rendering is important, or where the lamp is used with other light sources, a designer should choose metal–halide lamps that are specially made for color stability. These lamps are designed not to vary in CCT more than 200 K over the lamp life. Finally, dimming or reduced output operation of metal–halide lamps is not normally recommended because of the very noticeable color shift that occurs when a lamp is dimmed.

(e) Lamp Ballasts

A metal–halide lamp will operate satisfactorily on a simple reactor ballast, although a separate ignitor is usually required to start the lamp. Such ballasts have a low power factor (about 50%), which is undesirable from the perspective of energy efficiency, wiring economy, electrical losses, and component heating. High-power-factor magnetic ballasts (pf > 90%) are also available. Magnetic ballasts are large, heavy, and often noisy. The last characteristic can be improved by the use of a potted (epoxy-filled) ballast. Electronic ballasts are also readily available, along with dimming and multilevel ballasts. As noted previously, dimming ballasts are not frequently used because of the large shift in lamp color that they cause.

14.15 SODIUM-VAPOR LAMPS

The highest-efficacy general-purpose HID source available is the high-pressure sodium lamp (HPS). The basic construction of this type of lamp is illustrated in Fig. 14.20, which shows schematic drawings of the design. Typical performance data for various types of HPS lamps are given in Table 14.8. Construction is quite different from that of a mercury-vapor or metal–halide lamp. The characteristic color of HPS lamps stems from the spectral absorption phenomenon of the sodium contained in the arc tube—with a resultant pronounced yellow-tinted light.

(a) Primary Characteristics of HPS Lamps

Standard HPS Lamps. The extremely low CRI (20–22) is not acceptable where any degree of color rendition is required, thus limiting the standard HPS lamp to use in exterior areas and for road lighting.

Color-Corrected HPS Lamps. Color can be improved considerably by increasing the pressure inside the arc tube. This causes some of the sodium in the arc to be reabsorbed, and the radiated light widens its spectrum into the red range (at the expense of efficacy and lamp life).

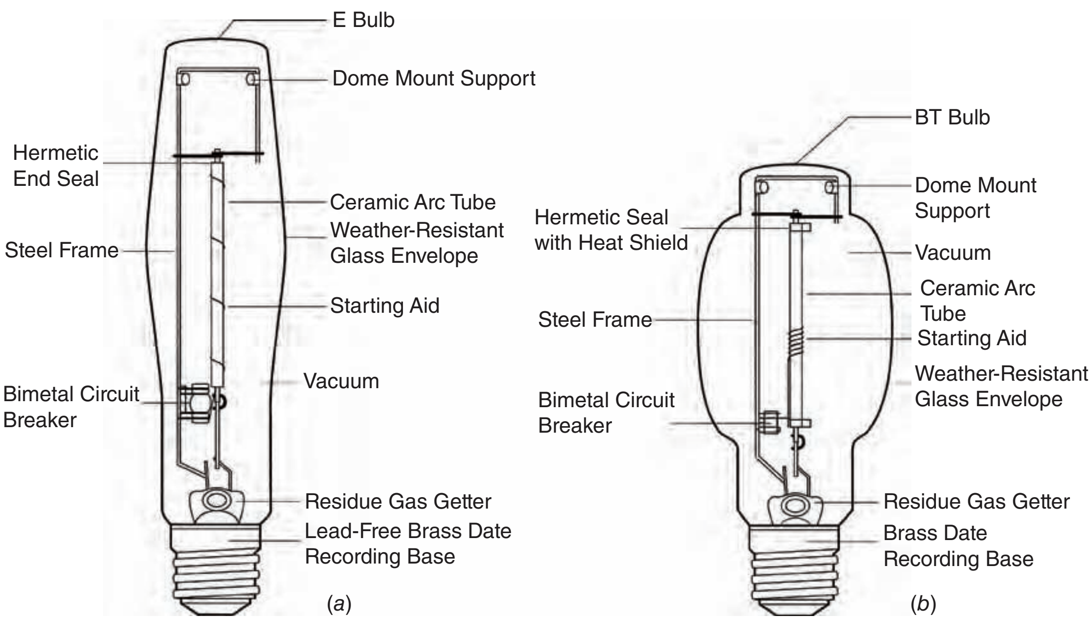


Fig. 14.20 *Simplified drawings of the internal construction of two high-pressure sodium (SON) lamp designs. (a) Noncycling lamp (in an E-shaped glass bulb) designed to indicate by a special color when the lamp has reached the replacement stage. Unlike standard HPS lamps, this lamp will not cycle on and off at the end of its useful life. (b) Retrofit HPS (SON) lamp in a BT bulb, intended for direct replacement of an existing mercury-vapor lamp. This lamp operates efficiently on a mercury-lamp ballast. (Drawings courtesy of Osram-Sylvania.)*

TABLE 14.8 Typical Data for Clear[a] High-Pressure Sodium-Vapor Lamps

Watts	Bulb[b]	Life (H)	Initial Lumens[c]	Lamp Efficacy (LM/W)[d]
"WHITE" LAMPS: CRI: 85, CCT: 2700 K				
35	T10	10,000	1250	36
50	ED-17	10,000	2000	40
100	ED-17	10,000	4200	42
COLOR-CORRECTED LAMPS: CRI: 60, CCT: 2200–2300 K				
100	ED-17	15,000	7300	73
250	ED-18	15,000	22,000	88
400	ED-18	15,000	37,000	93
STANDARD HPS LAMPS: CRI: 22, CCT: 1900–2100 K				
50	ED-17	24,000+	4000	80
100	ED-17	24,000+	9500	95
250	ET-18	24,000+	28,000	112
400	ET-18	24,000+	48,000	120
750	BT-37	24,000+	110,000	147
1000	E-25	24,000+	133,000	133

Note: Data extracted from current manufacturers' catalogs.

[a]Data are identical for coated lamps except for bulb shapes and lumen output.

[b]Other bulb shapes are available in some sizes. See Fig. 14.15 for bulb data.

[c]Initial lumens for coated lamps are 6% to 9% lower.

[d]Based on initial lumens. Efficacy with ballast is approximately 10% lower.

"White" HPS Lamps. A still greater increase in lamp pressure improves lamp color and yields a "whiter" lamp color in a limited wattage range. These low-wattage, reduced-efficacy, shortened-life lamps are normally operated with small, lightweight electronic ballasts.

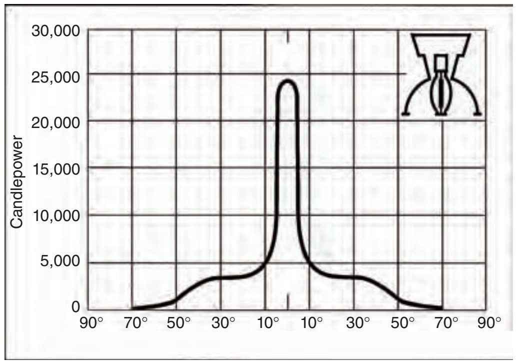
Because of its high output and narrow linear arc tube, any HPS lamp is a potential glare source, and lamps of 150 W or higher must be either completely shielded or mounted at sufficient height (if in an open reflector) to be above the near field of vision. These glare-prevention strategies also apply to metal–halide lamps.

If a diffusing coating is added to a sodium-vapor lamp, the entire glass envelope becomes the light-emitting source. This drastically reduces lamp luminance, and therefore glare potential, but also reduces output (and efficacy) by 6% to 8%. Light distribution from a coated lamp in an open reflector is vastly improved, as can be seen in Fig. 14.21.

(b) Other Operating Characteristics

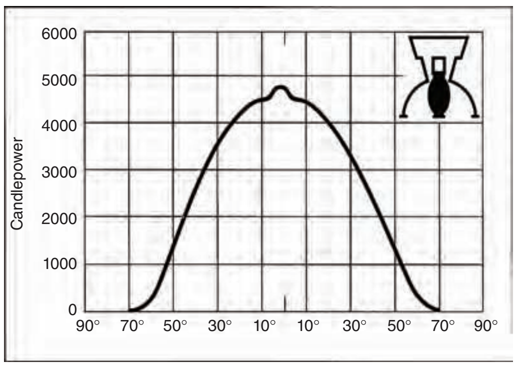
In contrast to mercury-vapor and metal–halide lamps, high-pressure sodium lamps do not emit any

(*a*)



Clear HPS lamp operating at 12,000 lumens in open-bottomed fixture.

(*b*)



Coated HPS lamp operating at 12,000 lumens in open-bottomed fixture.

(*c*)

Fig. 14.21 *(a) HPS retrofit and noncycling lamps. (b) The narrow linear arc tube of an HPS lamp is not suitable for use in an open reflector designed for a larger source such as a phosphor-coated mercury lamp. (c) A coated HPS lamp creates a large, diffuse source with improved light distribution. (Drawings courtesy of Osram-Sylvania.)*

appreciable UV radiation, do not tend to rupture violently, and can be installed in any position without affecting operating characteristics.

HPS lamps require a ballast for ignition and arc control. Due to the extremely high voltage required for lamp ignition, both magnetic and electronic ballasts contain an electronic ignition circuit. Because of this, an HPS lamp *must* be used with a compatible ballast that carries the same ANSI designation as found on the outer glass bulb. If used with an incompatible ballast (and fixture), the lamp may rupture and constitute a serious safety hazard. As with metal–halide lamps, ballasts for HPS lamps are available that provide instantaneous restrike after a power interruption. Light output on restrike is inversely proportional to the length of the outage; for example, after a 10-second outage, restrike light output will be 85% of full capacity, whereas after a 2-minute outage, lamp output will be only 10%. It takes approximately another minute to regain full output.

(c) Lamp Design Types

In addition to standard HPS lamps, including the color-corrected types, three additional special lamps have been developed to solve specific problems. They are:

1. *Noncycling lamp.* As an HPS lamp ages, its arc voltage rises. Eventually, the ballast is unable to sustain the arc, and the lamp extinguishes. After cooling, the lamp lights to full brightness and soon thereafter extinguishes again. This on–off cycling is characteristic of an HPS lamp at the end of its life. To eliminate this condition, a special noncycling lamp was developed that uses very little sodium amalgam in the arc tube and is more environmentally friendly because of this reduced content. To enhance this environmental aspect, these lamps are made with a lead-free base and lead-free solder. Photometric characteristics are similar to those of standard lamps. The lamps in Figs. 14.20*a* and 14.21*a* are of this design.
2. *Standby lamps.* As noted previously, HPS lamps require a minute or more to restrike after being extinguished. A crowded public area plunged into complete darkness is a recipe for disaster; therefore, such areas must always be furnished with instant-on emergency lighting. Standby lamps have two arc tubes. When the lighted one is extinguished due to a momentary power loss, the second (cool) arc tube immediately begins to glow—assuming that voltage has returned. This arrangement *may* be acceptable to some code authorities as a substitute for instant-on replacement lighting following a momentary power outage. It is *not* acceptable as emergency lighting as required by NFPA 101: *Life Safety Code*.
3. *Retrofit lamps.* These HPS lamps are designed as a direct replacement for mercury-vapor lamps of the same wattage. They are enclosed in BT-shaped bulbs of the same size as the lamp being replaced, and they operate properly on mercury-vapor lamp ballasts. A retrofit lamp is illustrated in Fig. 14.21.

14.16 LOW-PRESSURE SODIUM LAMPS

The low-pressure sodium (SOX) lamp produces light characteristic of sodium's monochromatic saturated yellow color, making it inapplicable for general lighting. Because of its very high efficacy of more than 150 lm/W, *including* ballast loss (but with a CRI of 0), it can be applied wherever color rendition is not an important criterion but energy efficiency is. Thus, SOX lamps are used for street, road, parking lot, and pathway lighting. SOX lamps are also used around astronomical observatories because the yellow light can be filtered out of a telescope. Another desirable aspect of SOX lamps is their 100% lumen maintenance. This, coupled with a high-intensity discharge lamp's typically long life (18,000+ hours), makes SOX lamps fairly economical in terms of life-cycle cost.

SOLID-STATE LIGHTING

The term solid-state lighting currently encompasses light produced by semiconductor light-emitting diodes (LED), organic light-emitting diodes (OLED), and polymer light-emitting diodes (PLED). Of these types, LEDs have emerged in recent years as a viable option to be looked at for architectural lighting applications. LEDs are the focus of this section, as OLED and PLED technologies are not yet mainstream.

14.17 LIGHT-EMITTING DIODES

Light-emitting diodes (LEDs), or light-emitting semiconductors, have been used since the 1960s in a wide range of applications—in medical instruments, bar coders, fiber-optic communication, mobile electronic technologies, consumer appliances, automotive instrument panels, signal lights, courtesy lighting, and transport signaling (traffic, rail, aviation). LED uses for architectural illumination have included signage, retail displays, emergency lighting (exit and emergency signs), and accent lighting for pathways. LED lamps and luminaires (Fig. 14.22) are sparking intense interest, however, and are seeing increased use in conventional building lighting applications. They are easy to install, last longer than incandescent or fluorescent lamps, are efficient (with good luminous efficacy values), and can provide good color rendering.

LED lamps are essentially micro light sources. A single-sided fire exit sign might involve the use of 100 individual LED lamps. Diffusion of this light source technology into mainstream architectural lighting applications requires the packaging of these point sources into larger area luminaires that can be used to illuminate a 1000 ft^2 classroom or a 15 m^2 office. This is happening (and rather rapidly). Manufacturers are bundling LEDs into architectural lighting products that allow designers to expand the use of this source beyond the market for accent or focus lighting.

The characteristics of LEDs that seem to stir the most interest are:

- Excellent longevity (some claims suggest 50,000 hours), although lumen maintenance over time is a concern as with other light sources
- Pretty good luminous efficacy (the excitement generated by LEDs would suggest huge leaps in efficiency beyond current sources; this is not the case)
- Directional light output (as opposed to the spherical light output of a conventional bulb-shaped lamp); this property can improve the effectiveness of an LED lighting installation
- Improved environmental friendliness relative to mercury-based lamps

As an emerging technology, LED products and applications should be considered with care. Many claims for performance have not been independently verified (or stood the test of time as with older lamp types). In several areas of performance (such as color rendering), it is not clear that existing metrics do a good job of dealing with LEDs. One area of concern in LED applications regards heat dissipation. Although reasonably efficient, LEDs are quite small and can experience heating problems not seen with larger lamps more exposed to ambient air. The U.S. Department of Energy (2013) has established the LED Lighting Facts program "to ensure that the LED products you find on the market meet your expectations for performance."

OTHER ELECTRIC LAMPS

14.18 INDUCTION LAMPS

An induction lamp is filled with low-pressure mercury vapor. When ionized by a high-frequency induction coil inside the lamp, the mercury vapor

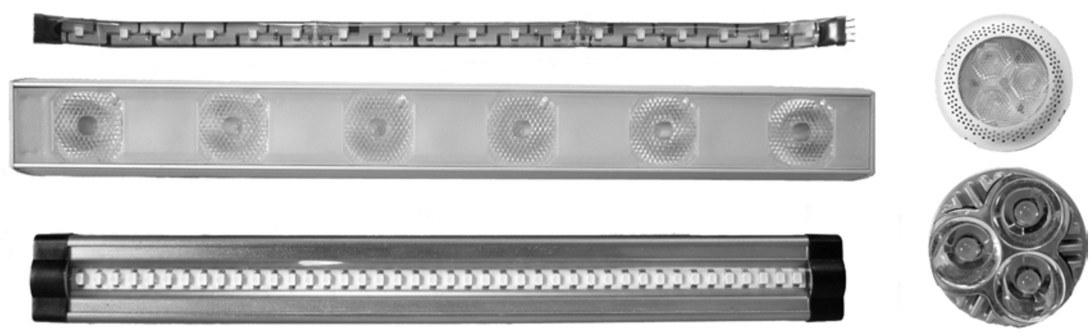


Fig. 14.22 Representative LED lighting fixtures.

produces UV radiation, which then strikes a phosphor coating on the inside of the lamp, producing light. This is similar to the light-producing process used by standard fluorescent lamps; the difference is that the gas is ionized by an induction coil (rather than an electron stream)—thus the name *induction lamp*. Two such designs are shown in Figs. 14.23 and 14.24

Characteristics of the lamp shown in Fig. 14.23 are as follows:

Wattage	85 W total, including external devices
Initial lumens	60,000
System efficacy	70 lm/W
CCT	3000 K or 4000 K
CRI	80+
Ignition time	Under ½ second
Time to 75% output	Up to 1 minute
Hot-restrike time after outage	Less than ½ second
Life (50% survival)	100,000 hours
Lumen maintenance	70% at 60,000 hours
Burning position	Any

The extraordinarily long life, excellent lumen maintenance, and instantaneous restrike time make the induction lamp suitable for illuminating public areas. As with all light sources, a comparison with other sources can only be made for a proposed usage based on project-specific considerations.

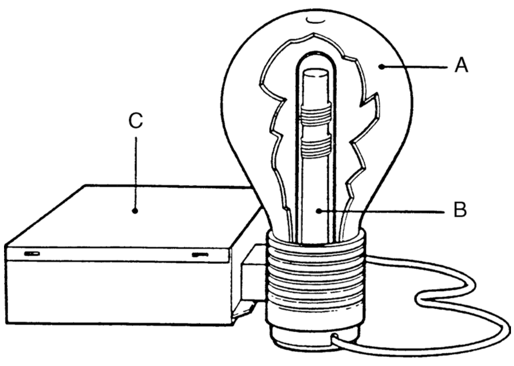


Fig. 14.23 *Schematic diagram of an induction lamp (rated 85 W, including all losses) showing the operating principles. The lamp is 4.3 in. (109 mm) in diameter and 7.5 in. (191 mm) high overall. The generator (C) produces a high-frequency current, which circulates in the coil on the power coupler (B). This ionizes the mercury vapor inside the lamp (A), producing UV radiation. The UV radiation strikes the fluorescent coating inside the lamp, producing light. (Illustration courtesy of Philips Lighting Company.)*

A self-contained induction lamp of lower wattage is illustrated in Fig. 14.24. This lamp is built into a modified R-shaped envelope with a standard Edison base, and is therefore readily applied as a direct replacement for a 100-W incandescent reflector lamp. The published performance values for the lamp are:

Total wattage	23 W
Initial lumens	1100
Efficacy	48 lm/W
CCT	3000 K
CRI	82
Life	10,000 hours
Lumen maintenance at 70% life	75%

14.19 SULFUR LAMPS

The principle of microwave energy excitation has been applied successfully to a lamp type that consists of a golf-ball-sized globe filled with an inert gas and a few milligrams of sulfur. In contrast to the induction lamp described previously, no mercury vapor is used in this lamp, and the radiation is full-spectrum light with very little ultraviolet or infrared radiation. A prototype lamp was a 6-kW unit that emitted more than 400,000 lumens (a lot of light). A more recent version of the lamp exhibited the following characteristics:

Total power input	1320 W
Initial lumens	130,000
Efficacy	101 lm/W
Diameter of globe	29 mm (1.1 in)
CCT	5600 K
CRI	80
Life of lamp (estimated)	60,000 hours
Life of exciting magnetron	15,000 hours
Lumen maintenance	Very high
Color constancy with aging	Excellent

Current sulfur lamp technology provides approximately the same output as a 1000 W HPS lamp, but with much better color characteristics. It also compares to about 1200 W equivalent of metal–halide lamp with similar efficacy, but again, because of its full-spectrum radiation, it has superior color characteristics. Initial trials of the lamp as a driver for a "light pipe" were successful.

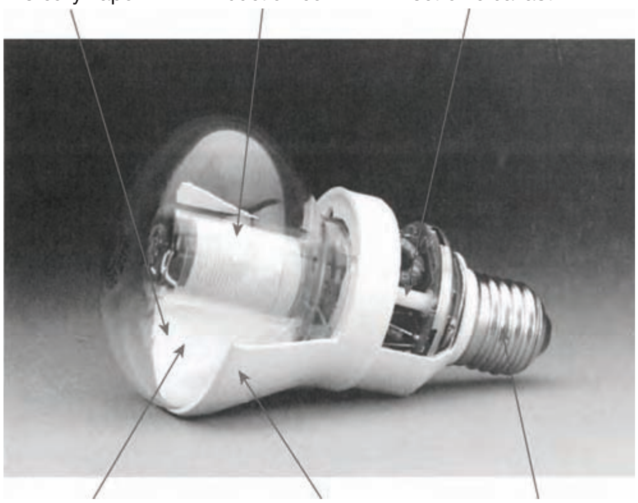


Fig. 14.24 *Cutaway of the GE induction lamp showing the essential elements: induction coil, phosphor-coated bulb with mercury-vapor fill, and electronic ballast. This 23-W lamp in a modified R (reflector)-shaped bulb has a height just under 5 in. (127 mm) overall and a 3-in. (76-mm) maximum bulb diameter. (Photo courtesy of GE Lighting.)*

14.20 FIBER OPTICS

Although optical fibers have been available since the 1920s, practical applications (in the medical field) were not developed until the late 1950s and early 1960s. Bundled fibers used as a diagnostic tool can deliver light to remote regions of the body and carry coherent (understandable) images back to a doctor. In recent years, fiber-optic systems have made their most significant advances in the communications field, wherein long-distance telephone cables and complex wire networks have been replaced by much simplified fiber-optic installations. Architectural applications of fiber optics have included alternatives that directly replace recessed ceiling downlighting, track and display case lighting in museums, and lighting for pools/spas, supermarkets, and other commercial buildings.

Illuminators for fiber-optic systems utilize a variety of lamp types. The primary advantages of using a fiber-optic system are that no heat is produced where the light exits the fiber (permitting "cool" lighting installations), and no UV radiation is transmitted through the fiber.

References and Resources

ANSI. 2011. ANSI C82.11, *High-Frequency Fluorescent Lamp Ballasts*. American National Standards Institute. New York, NY.

ANSI. 2002. ANSI C78.1451, *Electric Lamps—Use of Protective Shields with Tungsten-Halogen Lamps—Cautionary Notice*. American National Standards Institute. New York, NY.

Eley Associates. 1993. *Advanced Lighting Guidelines: 1993* (EPRI TR-101022s Rev. 1). Electric Power Research Institute. Palo Alto, CA.

Federal Energy Management Program (HID electronic/dimming ballasts). http://energy.gov/eere/femp/articles/new-and-underutilized-technology-hid-electronicdimming-ballasts//

IESNA. 2011. *The Lighting Handbook*, 10th ed. Illuminating Engineering Society of North America. New York, NY.

Krochman, J. 1963. "Uber die horizontal Beleuchtungsstarke der Tagesbeleuchtung." *Lichtechnik*, Vol. 15, No. 11.

U.S. Department of Energy. 2013. LED Lighting Facts. www.lightingfacts.com/

U.S. Environmental Protection Agency, Energy Star–labeled lamps and luminaires. http://www.energystar.gov/index.cfm?c=lighting.pr_lighting

CHAPTER 15

Lighting Design Process

15.1 GENERAL INFORMATION

LIGHTING DESIGN IS A COMBINATION OF APPLIED ART and applied science. There can be many solutions to the same lighting problem, all of which will satisfy the minimum project requirements, yet some will be dull and pedestrian, whereas others will display ingenuity and resourcefulness. The competent lighting designer approaches each problem afresh, bringing to it knowledge of current technology, as well as years of background and experience—thus, rarely being satisfied with a carbon copy of a previous design. It is these years of experience—coming from lessons learned via successful and not so successful designs—coupled with a constant striving for improvement, that differentiates the successful lighting consultant, designer, or engineer from the person who attempts to force each new job into the unwilling mold of a previous design.

Because of the large number of interrelated factors that affect the perception and performance of a lighting solution, no single design is the correct one. For this reason, it is not entirely desirable to solve a lighting problem using a step-by-step linear technique. However, experience has shown this technique to be a good approach for those who lack the experience necessary to envision an entire solution at once; thus, we have adopted it herein.

15.2 GOALS OF LIGHTING DESIGN

Simply stated, the goal of lighting is to create an effective, efficient, and pleasing luminous environment. These requirements—that is, utilitarian and aesthetic—are not antithetical, as is demonstrated by every good lighting design. Put simply, light can and should be regarded as a primary architectural material. Some fundamentals underlying lighting design are listed here:

1. Illuminance levels should be adequate for effective viewing of the particular task involved.
2. Variations (within acceptable luminance ratios) in a given field of view are desirable to avoid monotony and to create perspective effects.
3. Lighting equipment should be unobtrusive but not necessarily invisible. Fixtures (luminaires) can be chosen and arranged in various ways to complement the architecture or to create dominant or recessive architectural features or patterns. Fixtures may also be decorative and thus enhance the interior design.
4. Lighting must have the proper quality, and be deemed appropriate by users. Accent lighting, directional lighting, and other highlighting techniques increase the utilitarian as well as the architectural quality of a space.
5. The entire lighting design must be accomplished efficiently in terms of cost and energy

use—the former being determined principally by life-cycle costs, and the latter by operating-energy costs and resource-energy usage. Both cost and energy-use limitations are, to a large extent, outside of the control of the designer, who often works within established constraints in these areas.

With these goals in mind, we can propose a lighting design procedure, keeping in mind that the order of steps shown is not necessarily the same in each lighting problem and that, since all factors are closely interrelated, it is often necessary to address several of the stages simultaneously before arriving at a decision.

It is appropriate to note at this point that the lighting design approach and procedure explained in this chapter are primarily analytic; that is, the design procedure establishes requirements primarily in numerical form and then manipulates the variables of: sources, fixtures, placement of units, and so on, to arrive at a design solution. There exists an alternative approach, frequently referred to as *brightness design*, in which the designer labels surfaces on a prospective plan/section of a space with desired luminances as established by a mental picture (or other means) and designs the lighting accordingly. This approach, which can be very effective, is highly intuitive and requires considerable prior experience on the part of the designer. For this reason, and because of the hands-on, trial-and-error fieldwork involved in the approach, we feel that it cannot be adequately explained, or outlined in detail, in a textbook, and therefore it is not presented here. An exception to this statement involves daylighting models—an analog design method. A primary purpose of such a model is to give the designer a visual/mental picture of the proposed space's brightness patterns, on the basis of which apertures, aperture treatments, and interior geometries and reflectances can be varied to achieve the desired light and shadow patterns (luminances and luminance ratios).

15.3 LIGHTING DESIGN PROCEDURE

(a) Project Constraints

The flow chart shown in Fig. 15.1, which presents a suggested lighting design procedure and its interactions, should be referred to throughout the necessarily lengthy discussion that follows, in order to maintain perspective. It is important that the reader be aware of job constraints and of the necessary interactions between the lighting designer and the larger design team. We deliberately emphasize this to demonstrate the interdisciplinary nature of lighting design in general, with a strong connection to HVAC and daylighting design in particular. This approach, which is most often referred to as the *systems design approach*, is followed throughout the discussion.

Item 5 of the list in Section 15.2 refers to constraints. These can be related to the owner-designer-user team and/or the jurisdictional authorities. In some detail, these are:

1. *Owner-designer-user group.* The owner establishes the cost framework in question—both initial and operating. Both of these may include a rent structure, which in turn determines and is determined by the space usage. If the owner is also the occupant, the cost factors change somewhat but remain in force. The architect determines the amount and quality of daylighting, as well as the architectural nature of the space to be lighted. Many of these parameters are detailed in the building program. The architect and lighting designer (who may be the same person) should interact in this aspect of building design. For projects that will include the building commissioning process, an owner's project requirements document will contain all this information (and more).
2. The jurisdictional and informational authorities *may* include:

   The AHJ (authority having jurisdiction; at a municipal, county, or state level)
   DOE—U.S. Department of Energy
   GSA—General Services Administration
   NFPA—National Fire Protection Association
   ASHRAE—American Society of Heating, Refrigerating and Air-Conditioning Engineers
   IESNA—Illuminating Engineering Society of North America
   NIST—National Institute of Science and Technology

Most of these are listed as "jurisdictional" because their guidelines and standards are accepted as best practice—that is, they are respected by those in the building professions. Local laws (and

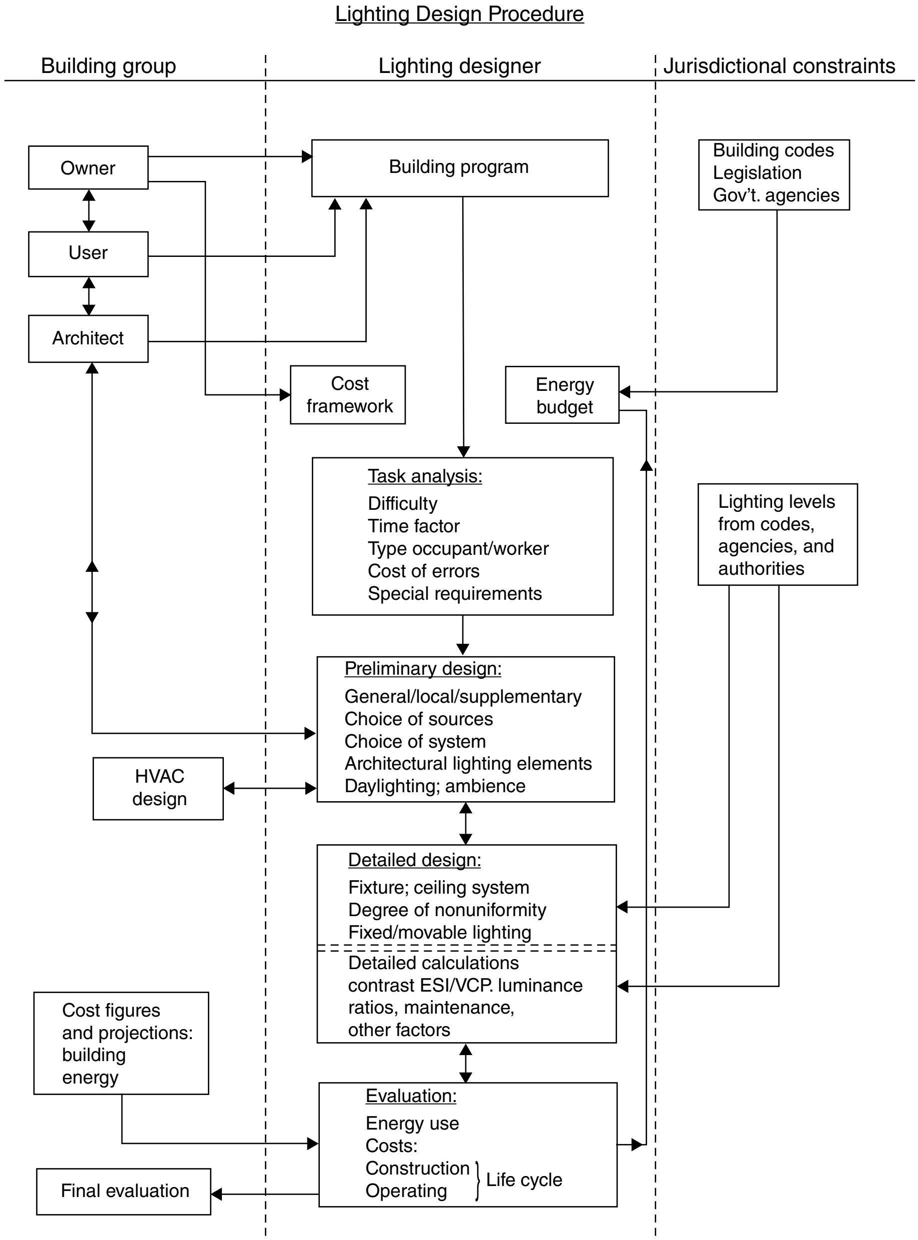


Fig. 15.1 *Lighting design procedure chart.*

the AHJ) will determine whether the lighting system in question must meet the requirements of ASHRAE, IESNA, and so on. If federal funds are involved, DOE/GSA standards will probably inform the design process. The principal areas of involvement are energy budgets and lighting levels, both of which affect every aspect of lighting design, including source type, fixture selection, fixture placement, and even maintenance schedules. For this reason, the first step in the lighting design procedure is to establish the project lighting cost framework and the project energy budget.

(b) Task Analysis

As shown in Fig. 15.1, this step essentially determines the needs of the project relative to the various visual tasks. Factors to be considered in addition to the general nature and location of each task are: its repetitiveness, variability, who is expected to be performing the task (physical condition of the user), task duration, cost of errors, and special requirements. Several of these factors have been discussed in the preceding chapters dealing with quality of light.

(c) Design Stages

These are the stages (preliminary and detailed) during which lighting proposals are raised, considered, modified, accepted, or rejected. This is also the most interactive part of the lighting design process, as is seen in Fig. 15.1. At its completion, a detailed, workable design is in hand. The critical interactions here are with the architect for daylighting, with the HVAC designer in terms of cooling loads, and with the electrical engineer relative to power loads. The first may result in changing spatial arrangements within the building, the second in coordinating lighting effects on the HVAC system (and sometimes vice versa), and the third in supporting the lighting design with power and controls. In brief, these stages consist of the following steps:

1. Select a lighting system. Select the type of light source and the distribution characteristic of the fixture(s), and consider the effects of daylighting, economics, and electric loads.
2. Calculate the lighting requirements. Use an applicable calculation method and establish the fixture pattern, considering the architectural effects.
3. Design the supplemental decorative and architectural (built-in) lighting.
4. Review the resultant design. Check the design for quality, quantity, aesthetic effect, and originality.

(d) Evaluation Stage

With a design proposal in mind, the design team can analyze it for conformance to the principal constraints of the owner's requirements (in particular, cost and energy). If the design stages have been carefully completed, with due attention to these factors, the results of the final evaluation should be positive. The results of this stage are given to the architectural group for use in the final overall project evaluation. In the following sections, we consider in detail each of the steps in the design procedure.

15.4 COST FACTORS

This is a particularly difficult item for a novice lighting designer because it requires experience in the field and an acquaintance with commercially available equipment. Also, the inevitable trade-offs between first cost and operating cost cannot be made intelligently unless the cost structure is clearly understood. The following guidelines should be of assistance both in avoiding unpleasant surprises when a job is estimated and in preparing cost analyses:

1. Decide at the outset what cost criteria will be applied—that is, the relative importance of first cost, operating costs, annual owning costs, and collective life-cycle costs.
2. Trade-offs are necessary between first cost and operating costs. For example, incandescent lamps and fixtures are low in first cost and high in operating cost. The inverse relationship between first and life-cycle costs is generally pervasive (although truly creative thinking may break the link). Dimming and control equipment decisions fall into this area of concern.
3. Manufacturers' catalog items are *always* cheaper than custom items and can be priced more readily and scheduled with more confidence.
4. Compare the annual owning costs of alternative systems or methods. Merging of these data into life-cycle cost comparisons is straightforward (see Appendix J).
5. The impact of lighting energy on the operating cost of the entire building must be studied and the apportionment of costs determined. The only practical means of accomplishing this is by using a computer simulation. Programs can be readily adjusted to reflect the effect of the lighting system on building costs and, in particular, on HVAC first cost and operating costs.

TABLE 15.1 Evolution of Lighting Power Density Values

SPACE TYPE	2013 LPD limit	2010 LPD limit	2007 LPD limit	2001 LPD limit
Dormitory	0.57 W/ft^2	0.6 W/ft^2	1.0 W/ft^2	1.5 W/ft^2
Hotel	0.87 W/ft^2	1.0 W/ft^2	1.0 W/ft^2	1.7 W/ft^2
Office	0.82 W/ft^2	0.9 W/ft^2	1.0 W/ft^2	1.3 W/ft^2
Retail	1.26 W/ft^2	1.4 W/ft^2	1.5 W/ft^2	1.9 W/ft^2

For LPD values in W/m^2, multiply the given values by 10.76.

Source: Reprinted with permission; ©ASHRAE, ASHRAE Standard 90.1-2013, ASHRAE Standard 90.1-2010, ASHRAE Standard 90.1-2007, and ASHRAE Standard 90.1-2001

It is incorrect to artificially separate design of the lighting system from design of the HVAC system, with which it intimately interacts.

The lower the lighting system's energy usage, the lower the building's overall operating cost. The argument that heat from a lighting system is fully utilized to heat the building and is therefore not wasted is a statement that does not take into consideration first costs and year-round operating costs of HVAC systems, the cost of lighting energy as well as lighting life-cycle costs, along with overall energy consumption. Even when, during certain seasons, the heat produced by lighting is beneficial for the building's overall performance, there is no advantage gained from not considering the efficient integration of said lighting systems into the larger building network. It is through critical integration that higher performance, higher efficiency, lower costs, and lower environmental impacts can be achieved.

15.5 POWER BUDGETS

The requirement to establish a project lighting power budget in accordance with a specified procedure has been incorporated into the building codes of most U.S. states and many countries.

The purpose of this budget determination procedure, as standards explicitly state, is not to dictate a design procedure. Instead, the purpose is to develop an overall maximum power budget within which the designer is free to do as he or she wishes. Outcomes are delimited, not methods. Energy extravagance in one area is necessarily at the expense of another area, because maximum power is inflexible, and the entire power budget is predicated on reasonable design techniques.

The accepted U.S. standard that defines the establishment of a lighting power budget is ASHRAE Standard 90.1, *Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings*, published by ASHRAE and regularly updated.

ASHRAE Standard 90.1 sets design requirements for the efficient use of energy in new buildings. Specifically excepted are small-scale residential buildings and buildings that use neither electricity nor fossil fuels.

Table 15.1 provides a few examples of lighting power density (LPD) values (using the building area method) from four recent editions of Standard 90.1. The values show the differences in "expectations" between various space types and also show a clear trend of increasing stringency over a decade-long period.

15.6 TASK ANALYSIS

This process establishes the quantity and quality of lighting required for each of the visual tasks in a building. The factors affecting these values, as shown in Fig. 15.1, are task difficulty, time factor, the occupant/worker/user, cost of errors, and special requirements. The Illuminating Engineering Society of North America (IESNA) *Lighting Handbook* (2011) presents detailed guidelines for lighting quantity and quality for a prodigious number of space types and tasks. This valuable resource is highly recommended.

(a) Difficulty

The components of visual difficulty are discussed at length in Sections 13.16 through 13.22, and the results in terms of recommended lighting levels appear in Tables 13.4 and 13.5. Essentially, the designer examines the task involved, and after determining the applicable authority for the project at hand, he or she selects the required illuminance(s).

In the absence of specific instructions or reasons to the contrary, the North American designer will typically use the IESNA recommendations. If there are several tasks to be performed at the same location and the most difficult one occurs infrequently, it may be reasonable to provide supplementary portable lighting or even to suggest moving the task to another location. If the most difficult task is the major task, the lighting design should be based on it and provision made for intensity reduction for less demanding work. As suggested by this discussion, illuminance within a building (or within a space) can vary with time and with location.

Variation in task difficulty is particularly common in spaces in public buildings. A school gym can be used for athletics, band concerts (despite the acoustics), testing, and town meetings—activities with totally disparate lighting requirements. In these and similar instances, it is common practice to treat the space as essentially four different spaces and to design lighting appropriate for each, while keeping a careful eye on maximizing common equipment usage. Fortunately, many multipurpose spaces do not have severe seeing tasks.

The task variation referred to here is the variation that occurs in one very specific location, and is not to be confused with task variation across an area, however restricted. Thus, a small private office of, say, 8 ft × 8 ft (2.4 m × 2.4 m) has a desk, file cabinet, and circulation space, involving three tasks of differing but constant difficulty in one small space. The corresponding lighting solutions for these lighting zones should vary with the task severity. The values listed in Tables 13.4 and 13.5 represent the required illuminance on the surface in question, whether horizontal, vertical, or in between. Design concern regarding adequate illuminance often focuses on a 30-in. (760-mm) high horizontal work surface. It is helpful in the early design stages to understand the ratio of horizontal-to-vertical illuminance for various lighting system approaches. This ratio is approximately

Narrow distribution (direct and semi-direct)	3:1
Wide distribution (direct and semi-direct)	2.5:1
General diffuse (indirect)	1.5:1

Once a design proposal is advanced, computer simulations can provide exact illuminance estimates for any desired surface, including important vertical surfaces.

Recommended design illuminance values assume adherence to both recommended luminance ratios and surface reflectances. It is necessary to select—in conjunction with the interior designer—finishes and reflectances for surfaces within all illuminated spaces. If, in a private office for instance, a dark wall finish of 10% reflectance is chosen, it will be necessary for the lighting designer to compensate for this by additional wall lighting to maintain the recommended maximum 10:1 brightness ratio (see Table 13.7 and the discussion of point I, item G, in Section 15.7). The atmosphere created by vertical surface luminances is discussed at a later point. Table 15.2 lists the reflectances of some common interior paint finishes.

(b) Time Factor

The length of time permitted for visual task accomplishment is important in exacting work and production situations (data entry, quality assurance, etc.). Compared to moderately difficult tasks—requiring a luminance of, say, around 170 cd/m^2 (50 fL)—prolonged intensive or rapidly changing tasks would require luminance (and thus usually illuminance) to be increased. Alternatively, the quality of light could be improved by increasing daylighting or improving task contrast (as a means of increasing equivalent

TABLE 15.2 Approximate Reflectance Values for Paints

Medium-Value Colors	Reflectance (%)
White	80–85
Light gray	45–70
Dark gray	20–25
Ivory white	70–80
Ivory	60–70
Pearl gray	70–75
Buff	40–70
Tan	30–50
Brown	20–40
Green	25–50
Olive	20–30
Azure blue	50–60
Sky blue	35–40
Pink	50–70
Cardinal red	20–25
Red	20–40

spherical illuminance without increasing raw illuminance).

(c) Occupant Factor

Inasmuch as the age and other specific characteristics of a worker/occupant are usually not specifically known, a "standard" person is typically presumed to be the viewer. This standard person is usually a college-age student (a willing audience for scientific studies and statistical normalizations). Basic illuminance recommendations are often established with such a standard user in mind. If there is likely to be a high percentage of older workers, as is the case in certain building space types or industries, lighting should be increased. This compensates for the inability of an aging eye to compete with younger eyes when it comes to visual acuity. In fact, any likely deviation from the "normal" user relative to lighting (or thermal or acoustical) design should be identified, considered, and acted upon (as necessary).

(d) Cost of Errors

This factor involves an economic trade-off between savings that result from improved visual acuity (accuracy) and the cost of improved lighting to reach the higher accuracy. Performance can be brought close to perfection, but the cost of so doing increases much more rapidly than the proportional increase in performance. Lighting is usually designed to provide approximately 90% accuracy. Thus, this analysis is basically an economic calculation, the criteria for which must come from the owner or client. Tasks in which this problem is encountered include inspection, proofreading, textile matching, very fine machining, and precision manufacturing.

(e) Special Requirements

These may include any nonstandard task lighting requirements. Examples are: a need for a specific light-source color, directionality for shadowing, reflections needed for inspections, polarization, and controlled variations (as in a space with varied tasks or a varying daylight factor). In addition, the physical dimensions of a task often create special requirements of their own. We tend to assume a small object in the horizontal plane because that is the normal office task. There are exceptions, however, such as an easel, a large machine, an inspection bench, or a cutting table. Consequently, these special requirements may arise:

1. *Large tasks.* With large tasks, the angle of view may vary from 20° to 70° from the vertical, resulting in radically changing reflection (glare) angles and reflection patterns.
2. *Three-dimensional tasks.* These tasks shadow themselves, particularly when containing undercuts and reveals. An architect's model shop presents such tasks. When it is necessary to see into an opening, an intense narrow beam is required.
3. *Tools.* Tools cast shadows below and in front when lighted from above and behind. A fabric cutter must see ahead of and below the cutting machine.
4. *Nonhorizontal tasks.* These must be analyzed for the plane in which they stand. As noted in Section 15.6(a), the ratio between horizontal and vertical illuminance can vary between 1.5:1 and 3:1, depending upon the lighting system. Task lighting requirements are stated in the plane of the task. This can have a pronounced effect on the selection of a lighting system and its spatial arrangement.
5. *Task observed from various positions.* There are instances in which a fixed task is observed from several angles, such as a drawing in a conference room, a wall display, or a sculpture. Illumination must be adequate for all viewing angles.

15.7 ENERGY CONSIDERATIONS

Energy considerations must pervade every aspect of the design process. Some background is in order to place the subject of lighting system energy in proper perspective. Best current estimates indicate that lighting consumes approximately 25% of the electric power generated in the United States. In terms of *resources*, this amounts to approximately 4 million barrels (462,500 kL) of oil per day. The same sources indicate lighting usage by occupancy as approximately:

Residential	20%
Industrial	20%
Retail	20%
Schools and offices	15%
Outdoor and other	25%

In commercial buildings, lighting consumes about 20% to 30% of electric energy; the percentage is greater in residences and lower in industrial facilities. A reduction of 40% to 50% in lighting energy is attainable through judicious design. Translated into resources, such a reduction can readily amount to more than 1 million barrels (115,630kL) of oil per day. Few will deny that such a goal is well worth the effort. In a mechanically cooled building, every 1.0 W/ft^2 (10.7 W/m^2) reduction in lighting energy will result in at least a 1.25 W/ft^2 (13.5 W/m^2) energy savings. Offices and schools (see, for example, Table 15.1) can be well lighted with less than 1.5 W/ft^2 (16.1 W/m^2). The question to be answered then is: What design guidelines can be followed in order to achieve energy-conscious design?

The following are general recommendations regarding the design of energy-efficient lighting systems. For specific lighting system energy design targets and details, refer to ASHRAE Standard 90.1 (ASHRAE, 2013), the *Advanced Energy Design Guides* published by ASHRAE (various dates), and LEED (USGBC, 2013). For lighting effectiveness guidelines refer to *The Lighting Handbook* (IESNA, 2011).

I. Concept-level approaches to energy-conscious lighting design include:

A. *Design lighting for expected activity.* This is the task lighting approach. It is energy-wasteful to light any surface to a higher level than required. Nonuniform lighting is recommended where high illuminance levels are required for selected tasks in multitask spaces. One way to accomplish this for areas where an exact furniture layout is not available is to use readily movable fixtures. Providing overall high-lux illumination with a provision for switching to reduced lighting levels is not advisable because of the increased first cost and the psychological impetus to operate at maximum levels. Another solution is to use fixed luminaires for general low-lux lighting and supplementary task lighting. Other factors and techniques to be borne in mind are:

1. Place tasks with similar lighting requirements in the same general location.
2. Place the most severe seeing tasks at the best daylighting locations.
3. Improve the quality of difficult visual tasks. This is more economical in terms of energy-use than providing additional light.
4. The advantages of nonuniform lighting increase as the space between workstations increases.
5. When using a task-ambient design approach, keep in mind that a nonuniform ceiling layout may give a chaotic appearance to a space. Therefore, the preferred approach is to use uniform ambient lighting and localized supplemental lighting.

B. *Use effective, high-quality, efficient, low-maintenance, thermally controlled luminaires.* "Effective" means providing useful light and minimizing direct glare. In cases where much of the viewer's time is spent in a head-up position, as in schools, or where the viewer can compensate for veiling reflections, the design should lean toward achieving high visual comfort probability. Where work and viewing position are fixed, and most of the viewer's time is spent head-down, the design should lean toward low reflected glare. The following should also be kept in mind:

1. A *high-quality* luminaire is made with permanent finishes such as Alzak® or multi-coat baked enamel or any of the high-quality permanent aluminum finishes currently available. This ensures that its performance after 8 to 10 years of service will be comparable to the original.
2. An *energy-efficient* luminaire is one with a high luminaire efficacy rating (LER). Higher LER (as with CU) translates directly into equal effectiveness at lower energy cost.
3. A *low-maintenance* luminaire will remain clean for extended periods and is designed so that all reflecting surfaces can be easily and rapidly cleaned without demounting. Enclosed fixtures should be gasketed. Nongasketed units collect and retain dust, thus causing rapid lumen output depreciation. Relamping should be simple

and rapid to encourage group relamping programs that are energy-efficient and cost-effective. A 20% increase in maintained light is possible if lamps are replaced at the end of their *useful* life—that is, when output is down to 70% of initial maintained lumens—and if fixtures are cleaned and maintained on a fixed schedule. No cost trade-off is generally involved because periodic maintenance and relamping are normally cheaper than one-at-a-time maintenance and burnout replacement, *and* they yield 20% higher average lumen delivery. Fixtures in relatively inaccessible locations such as high ceilings must be designed for low maintenance, and maintenance should be on a fixed schedule. The role of the LLF (light loss factor) in illuminance analysis shows the importance of reducing the impact of this variable to the lowest reasonable condition—first cost and energy costs both benefit.

4. A *thermally controlled* luminaire controls the heat generated by the light source (Fig. 15.2). This effect depends to a large extent on the type of HVAC system, the lighting heat load, and the types of fixtures being considered. Detailed analysis of this factor involves HVAC design and the overall impact of lighting energy on the building. In the late 1980s, the light-heat problem was principally directed at expeditiously removing luminaire heat. Today, the use of electronic ballasts and low-wattage lamps has reduced the seriousness of this problem.

C. *Use efficient light sources and accessories.* This point is self-explanatory. The ready availability of high-efficacy, high color rendering index (CRI) light sources has made this factor far less problematic than previously. The only cost trade-off involved is between relatively expensive, high-CRI sources and lower-cost, low-CRI sources. The cost differential is not large, so the choice of source is not heavily influenced by economic factors.

The advent on the market of LED light sources and fixtures and the ongoing (in the U.S.) hand-wringing about incandescent sources suggest that light source economics

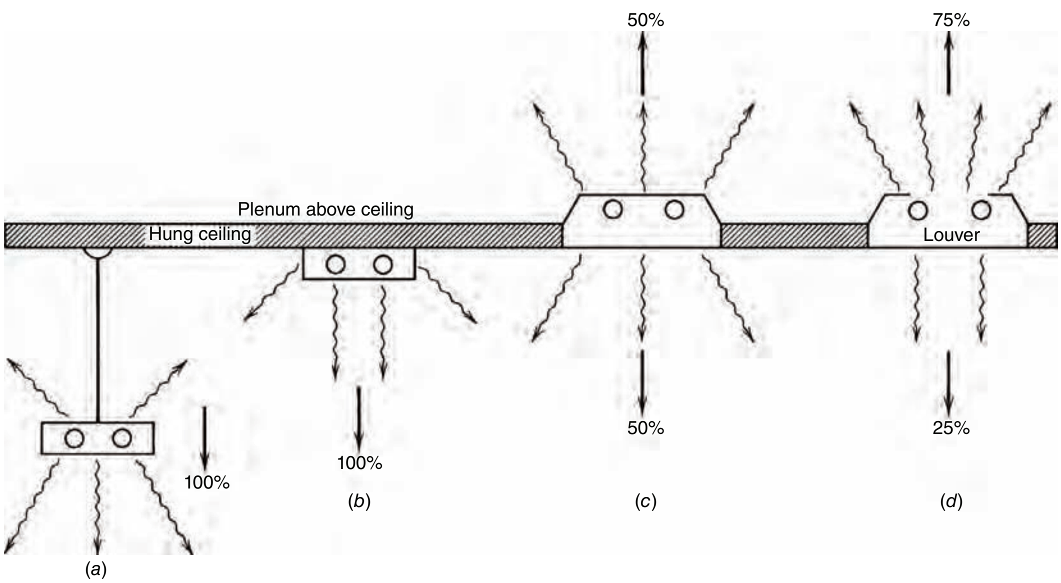


Fig. 15.2 *Method of fixture installation controls the transfer of heat from a luminaire. (a) Suspended units transfer all heat to the space while remaining fairly cool. (b) Surface-mounted fixtures also transfer all heat to the space but, because of blocked transfer upward, run hot. (c) Completely enclosed recessed units transfer about 50% of their heat to the plenum. (d) Open-louvered, baffled units transfer about 75% of their heat. When they are ducted, heat transfer upward can be as high as 85%.*

be looked at carefully for any innovative or unconventional project—where cost lessons from the past are likely no longer applicable.

Spill light and borrowed light are often neglected sources. For example, clerestory fenestration along corridors between offices can take advantage of borrowed office light in order to establish sufficient corridor lighting.

D. *Select an appropriate lighting system.* As detailed in Sections 15.10 to 15.15, there are five general approaches to light delivery, each with its particular distribution characteristics and, therefore, applicability. In addition, luminaires must be carefully located to provide uniformity of ambient lighting, where applicable, and good distribution of task lighting. When using indirect luminaires, correct spacing and hanging distance will avoid ceiling "hot spots," which can cause direct and reflected glare. Properly designed indirect lighting allows fully effective use of a space, in that users are not forced to face in any particular direction in order to avoid direct or reflected glare caused by fixtures. The mounting height of suspended fixtures must be coordinated with cavity sizes and finishes to decrease unnecessary light loss and maximize coefficient of utilization.

E. *Use daylight, and use it properly.* Daylight must be considered as a basic light source that is subject to both weather variations and time variations. A three-shift industrial plant cannot use daylight on all shifts, but it can for at least one shift—lighting design should address this fact. Part of proper daylight design is control of window luminance, which can cause severe and even disabling glare. A corollary of excessive luminance is excessive heat gain—both of which are manageable with common manual and automatic control devices. Window control devices should be designed to reflect light back into a space at night to avoid light loss through transparent windows.

F. *Use energy-efficient lighting control strategies.* The subject of lighting control, including manual and automatic switching, dimming, sensing, and intensity control, for both new installations and retrofit work, is covered in Sections 16.13 to 16.17. Proper design of controls can reduce energy consumption over a noncontrolled installation by as much as 60% without reducing lighting effectiveness. Appropriate controls are mandated in ASHRAE Standard 90.1.

G. *Use light finishes on ceilings, walls, floors, and furnishings.* This point is repeatedly emphasized in this book. A brief summary of recommended reflectance ranges is:

Ceilings	80–92%
Walls	49–60%
Furniture, office machines, and equipment	25–45%
Floors	20–40%

In addition to producing higher illuminance levels in a room, high reflectances minimize uncomfortable luminance ratios between, for instance, luminaire and upper wall, or task and background. Suggested maximum luminance ratios are:

1. Between task and near surround—3:1
2. Between task and immediate area—10:1
3. Between luminaires and their background—20:1
4. Anywhere in the normal field of view—40:1

Note that these targets are *maximum values*, and ratios above these limits should be accepted only with excellent justification.

II. Detailed requirements, generally from ANSI/ASHRAE/IESNA Standard 90.1, include:

A. *Mandatory requirements* (summarized, as they are extensive):

1. All interior and exterior lighting must conform to stated energy budget limitations. Trade-offs between the exterior and interior are not permitted.
2. Buildings shall have some form of automatic lighting shutoff control.
3. Where applicable, occupancy sensors and automatic daylight compensation controls should be used.

4. Separate spaces must have separate controls.
5. Enclosed rooms should have controls that allow for at least two lighting levels.

B. *Recommendations*:

1. Where task/ambient lighting is used, in order to avoid uncomfortable luminance ratios, the ambient level should not be lower than a third of the task level
2. Accent lighting should not exceed five times the ambient lighting level. Therefore, in merchandising areas where the contrast between ambient and task levels is critical, ambient levels should be reduced as much as is practical.
3. When specifying superreflective aluminum in fluorescent (or other) luminaires, determine that the material's high reflectance will be maintained in the specific application and that the recommended luminaire maintenance procedures can and will be implemented.
4. Utilize low-energy/low-maintenance exit signage where permitted by local codes; such equipment is readily available.

The energy-efficiency benchmarks in ANSI/ASHRAE/IESNA Standard 90.1 are updated on a regular basis (roughly every three years). The current version of this standard should always be used for design. The accompanying *User's Manual* (ASHRAE, 2011) is recommended as a valuable supporting document to assist with interpreting and implementing Standard 90.1.

15.8 PRELIMINARY DESIGN

The preliminary design phase (Fig. 15.1) is the time during which ideas crystallize, in terms of areas, patterns, as well as light and shadow, but not yet in terms of hardware. At this stage of the process, the intended quality of the system is determined—that is, desired illuminances, luminances, diffuseness, color rendering, energy efficiency, glare limits, and relationship of vertical to horizontal lighting. The last factor establishes in large measure the "mood" or lighting ambience of a room. In the sections that follow, the quality of each is considered, and applications are suggested. The ultimate quality of the lighting system, however—composed of visual pleasantness, centers of visual attention, highlights and shadows, as well as texture and forms—requires a deft and artistic combination of the previously mentioned considerations. A few observations in regard to this subject, not covered elsewhere, are mentioned in the following paragraphs.

Planes other than the working plane must always be considered. The ratio of vertical illuminance to horizontal illuminance of a chosen lighting system determines wall luminance, which in turn greatly influences the overall impression of spatial brightness. The floor finish has a pronounced effect on ceiling brightness with direct lighting systems because ceiling illumination in direct systems derives only from room interreflectances, with floor reflectance being particularly important in large spaces.

The chromaticity (wavelength distribution) of room lighting depends primarily on the source but secondarily on the luminaire and surface reflectances. A "white light" source can be tinted slightly by the use of a colored reflector in the luminaire; the effect on luminaire output of such a decision must be considered. In the case of semi-indirect and indirect lighting, the same effect can be accomplished by the use of colored ceiling and upper wall surfaces, which serve as secondary reflectors and become an actual luminous source for the room.

15.9 ILLUMINATION APPROACHES

The discussion that follows primarily addresses electric lighting systems. The descriptions apply directly to lighting fixtures and fixture arrangements. Similar considerations, however, can be seen to apply to daylighting design—and the implications of these considerations on daylighting design should not be overlooked during the design process.

There are three broad approaches to illuminating a space: general, local/supplementary, and combined general and local.

(a) General Lighting

This is a system designed to provide uniform, and generally although not necessarily, diffuse lighting throughout the area under consideration. The methods of accomplishing this result range from the use of luminous ceilings to modular direct or indirect luminaires (using a wide variety of lamp types), to properly spaced and chosen recessed downlights. The key is that the resultant illuminance on the working plane must be reasonably uniform. This type of lighting distribution is appropriate for a variety of spaces—in particular those where the task may be located anywhere on the work plane (such as a classroom with movable desks, a chalkboard, a bulletin board).

(b) Local/Supplementary Lighting

These two terms are used interchangeably. By definition, both *local lighting* and *supplementary lighting* provide a restricted area of relatively high intensity. A desk lamp, a high-intensity downlight on a merchandising display, and track lighting illuminating wall displays are in practice all referred to as *local*, *supplementary*, or *local/supplementary* lighting. Typical of this genre are the units illustrated in Fig. 15.3.

(c) Combined General and Local Lighting

This illumination approach is used in spaces where the general visual task demands are low-lux, but supplementary lighting is required in a limited area for a particular task.

These three basic approaches to distributing light can be accomplished in many ways by the use of luminaires and lamps of different types. The

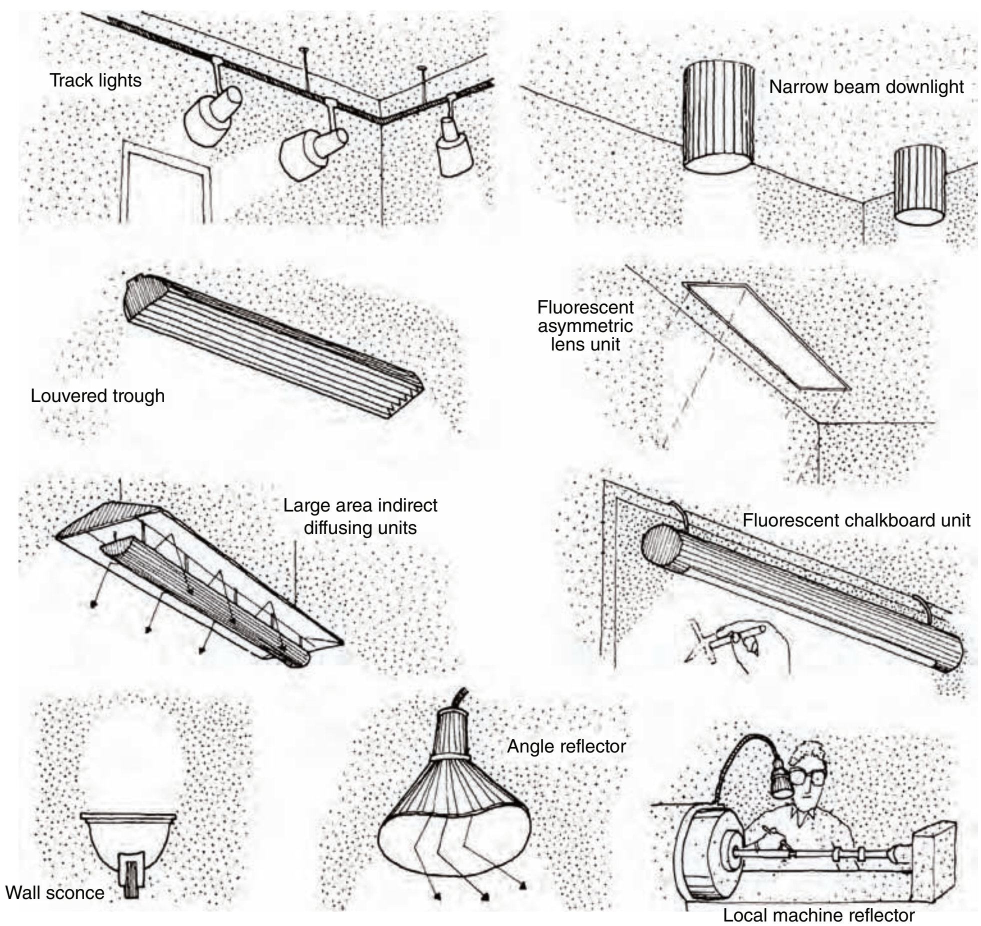


Fig. 15.3 *Typical supplementary lighting units for incandescent, CFL, and linear fluorescent sources.*

illumination *method* is a function of both luminaire arrangement and the luminaire's inherent lighting distribution. The term *lighting system* is used to describe the combination of a particular lamp type and fixture type, applied in a particular way. Thus, a reflector-type fixture, when aimed down, gives *direct* light. The same fixture, when beamed up at the ceiling, gives *indirect* light. The following section describes the systems that constitute the vast majority of lighting installations.

15.10 TYPES OF LIGHTING SYSTEMS

No single lighting system can be said to be the only viable choice in a given circumstance; on the contrary, a designer normally has a choice of at least two systems that, if utilized properly, will yield illumination of adequate quantity and good quality. Other factors, however, such as harmonization with the architecture, costs, and other variables, usually tip the balance in favor of one system or the other.

The five generic types of lighting systems are indirect, semi-indirect, diffuse or direct–indirect, semi-direct, and direct.

15.11 INDIRECT LIGHTING

Between 90% and 100% of the light output of the luminaires (see Fig. 15.4*a)* is directed toward the ceiling and upper walls of the room. The system is

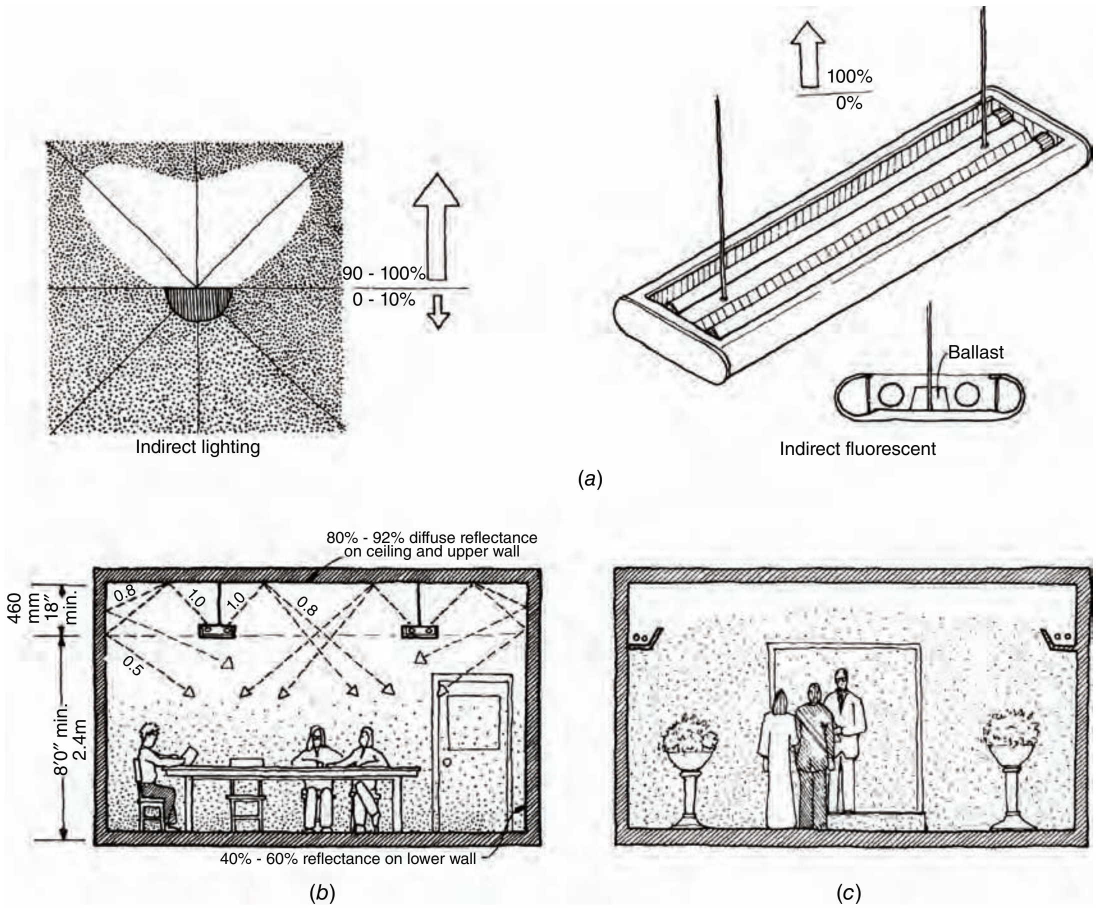


Fig. 15.4 *Indirect lighting. (a) The luminaires deliver 90–100% of their output above their own horizontal plane. (b) The ceiling and upper wall surfaces of the space are directly illuminated, and by reflection become large secondary sources that illuminate the space below. When properly designed, this type of installation yields a substantially uniform bright ceiling. (c) Use of architectural coves gives an acceptable luminance gradient on the ceiling and, if properly designed, nearly uniform, glareless illumination in the room. This system of illumination is particularly useful in spaces with digital screens.*

called *indirect* because practically all the light reaches a horizontal working plane indirectly, that is, via reflection from the ceiling and upper walls. The ceiling and upper walls in effect become a secondary light source, and if these surfaces have high-reflectance finishes, the room illumination becomes highly diffuse (shadowless). Because the source must be suspended at least 12 in. (300 mm), and preferably 18 in. (450 mm) or more from the ceiling (depending on the fixture output) in order to avoid ceiling "hot spots," this system requires a minimum ceiling height of 9 ft 6 in. (~3 m). If luminaires are correctly spaced, the resulting illuminance is uniform, and direct and reflected glare potentials are minimal.

To avoid an excessive luminance ratio between the luminaire and its surrounding field, the luminaire can be made translucent on the bottom, the sides, or both. Approximately 750 lux (75 fc) is the maximum horizontal-plane illuminance attainable without exceeding an *overall* ceiling luminance of about 2500 cd/m^2 (730 fL) (see Section 13.28). With practically no veiling reflections, this illuminance is sufficient for all but the most difficult tasks. The lack of shadow, low source brightness, and highly diffuse quality created by indirect lighting give a very quiet, cool ambience to a space, suitable for private offices, lounges, and waiting areas. Areas having specular visual tasks, such as an office with digital screens, use this system to great advantage. In such spaces, indirect fixtures *without* luminous bottoms or sides should be specified.

When properly designed, particularly when the source of light is integrated with architectural coves (see Fig. 15.4*c*), the ceiling has a floating sky quality, which is pleasant and can be used to give an impression of height in a low-ceilinged room. (This system is not to be confused with a trans-illuminated ceiling, which is really a direct lighting system of entirely different quality and effect.) A further characteristic of the indirect lighting system is a loss of texture on vertical surfaces, as is common to all fully diffuse lighting.

Indirect lighting is inherently inefficient, because much of the useful light reaches the working plane only after at least two reflections—within the luminaire and off the ceiling/upper wall. However, to a considerable extent this inefficiency is offset by the glare-free nature of the lighting—if the improved lighting quality allows for a reduction in target illuminance.

15.12 SEMI-INDIRECT LIGHTING

With this system, between 60% and 90% of luminaire light output is directed upward to the ceiling and upper walls. This distribution is similar to that of indirect lighting, except that it is somewhat more efficient and allows higher levels of illumination without undesirable brightness contrast between the luminaire and its background, along with lower ceiling brightness. A typical fixture, illustrated in Fig. 15.5, employs a translucent diffusing element through which the downward light component passes. The ceiling remains the principal light source, and the diffuse character of room lighting remains. Direct and reflected glare are both very low, as they are with indirect lighting (see Fig. 13.36). With both indirect and semi-indirect systems, it is often desirable to add accent lighting

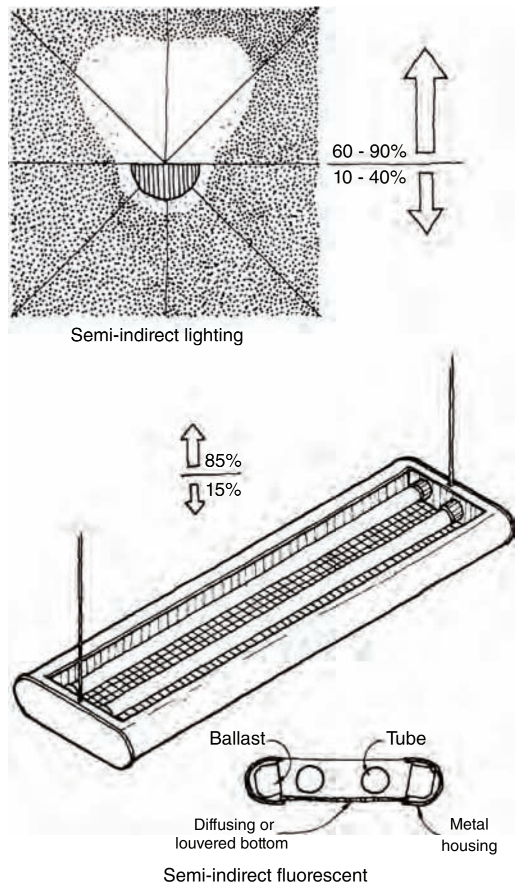


Fig. 15.5 *Semi-indirect lighting.*

or downlighting to break the monotony inherent in these systems and establish visual points of interest.

The light in both indirect and semi-indirect lighting systems undergoes a number of ceiling and wall reflections before reaching the horizontal working plane. The use of colored paints, particularly on the ceiling, can serve to tint the room illumination slightly via selective absorption—to either good or bad effect, depending upon the space in question.

15.13 DIRECT–INDIRECT AND GENERAL DIFFUSE LIGHTING

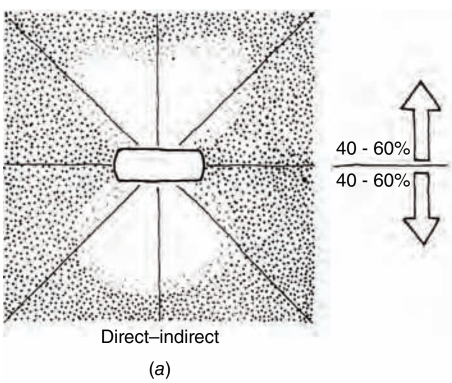
Direct–indirect lighting provides an approximately equal distribution of light upward and downward, resulting in a fairly bright ceiling and upper wall (Fig. 15.6). For this reason, luminance ratios in the upper-vision zone are usually not a problem. As the ceiling is an important (although secondary) source of room illumination, diffuseness is substantial, with resultant satisfactory vertical-plane illumination.

General diffuse fixtures (Fig. 15.7) distribute light in all directions, whereas direct–indirect fixtures have little or no horizontal component. Suspension stems for both types should be of sufficient length to avoid excessive ceiling brightness, generally not less than 12 in. (305 mm).

Because the impression of illumination depends, to a large extent, on *wall luminance* (because this is the surface we see most often), a space with general diffuse illumination *appears* brighter than one with direct–indirect illumination due to the darker walls in the latter (see Figs. 15.7*b* and 15.11).

The potential for both direct and reflected glare can be minimized by avoiding excessively bright luminaires and giving attention to the positioning of sources and viewing angles. Furthermore, because a luminaire (like any other luminous source in the field of view whose luminance is higher than that of the average scene) draws the eyes' attention, particular care must be taken to limit its luminance and to avoid disturbing fixture patterns (see Fig. 15.14).

The efficiency of these two systems is good. Both are well applied in spaces requiring overall uniform lighting at moderate levels, such as



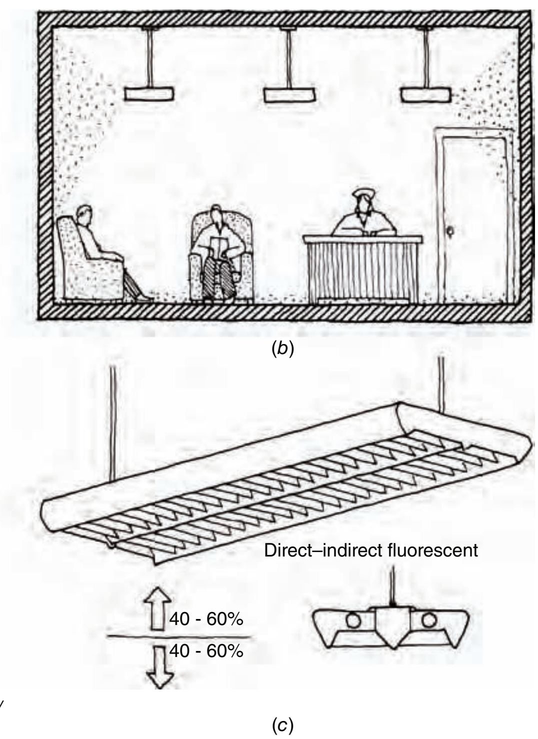


Fig. 15.6 *(a) Direct–indirect lighting. Upper and lower room surfaces are luminous (b), but the center of walls is not because of the lack of horizontal light output from fixtures (c). The majority of light on the working plane comes directly from the luminaire.*

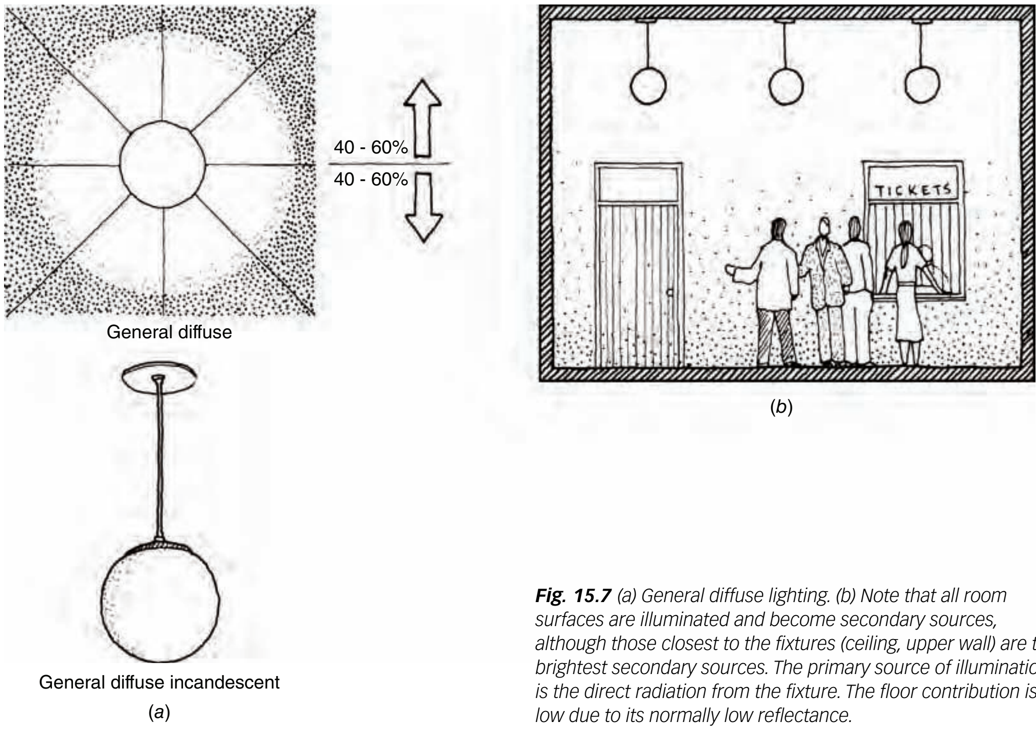


Fig. 15.7 *(a) General diffuse lighting. (b) Note that all room surfaces are illuminated and become secondary sources, although those closest to the fixtures (ceiling, upper wall) are the brightest secondary sources. The primary source of illumination is the direct radiation from the fixture. The floor contribution is low due to its normally low reflectance.*

classrooms, standard office work spaces, and merchandising areas.

15.14 SEMI-DIRECT LIGHTING

In this type of lighting system, 60% to 90% of the luminaire output is directed downward, with the remaining upward component serving to illuminate the ceiling (Fig. 15.8). If the ceiling has a high reflectance, this upward component is normally sufficient to minimize direct glare from the luminaires, depending on eye adaptation level. The degree of diffuseness depends largely on the reflectances of room furnishings and of the floor. Shadowing should not be a problem when the upward component is at least 25% and ceiling reflectance not less than 70%. With lesser upward components, the system is essentially a direct lighting system (see Section 15.15). The semi-direct system is inherently efficient. Reflected glare can be controlled by the methods discussed in Section 13.29. With adequate wall illumination, the quality of the lighting gives a pleasant working atmosphere. It is applicable to offices, classrooms, shops, and other working areas.

15.15 DIRECT LIGHTING

In this system essentially all the light from a luminaire is directed downward. As a result, ceiling illumination is entirely the result of light reflected from floor and room furnishings. This system, more than any other, requires a light, high-reflectance, diffuse floor, unless a dark ceiling is specifically desired. Occasionally, ceilings are deliberately painted a dark color and subsequently complemented with pendant-mounted direct fixtures, so as to lower the apparent ceiling height, in order to correct a poorly proportioned room, or to hide unsightly piping, ductwork, and so on.

The effect of direct lighting depends greatly on whether the luminaire light distribution is spread out or concentrated (Figs. 15.9 and 15.10). In the former case, considerable diffusion of light results

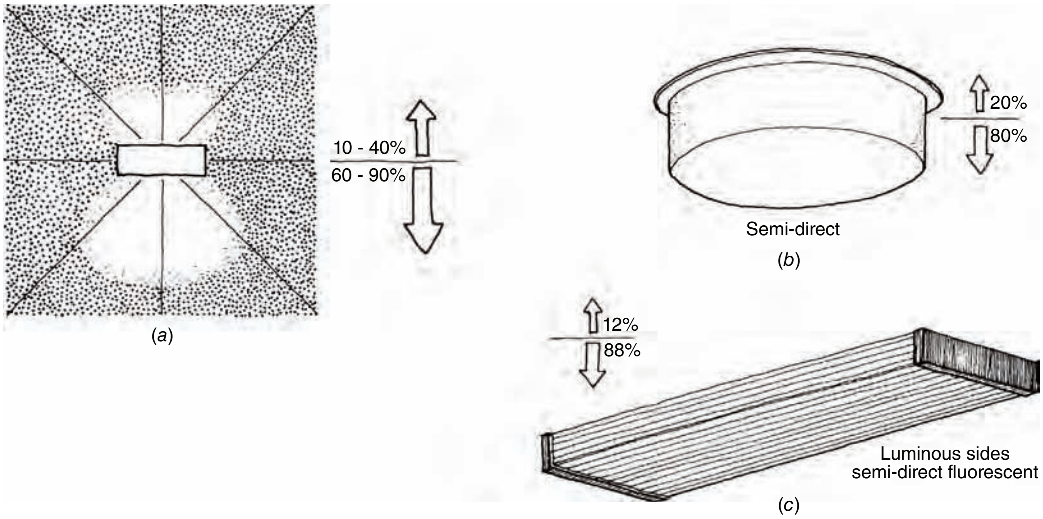


Fig. 15.8 *Semi-direct lighting provides its own ceiling brightness (a), with surface-mounted fixtures (b) or pendant/surface units (c). Other characteristics are similar to those of direct lighting.*

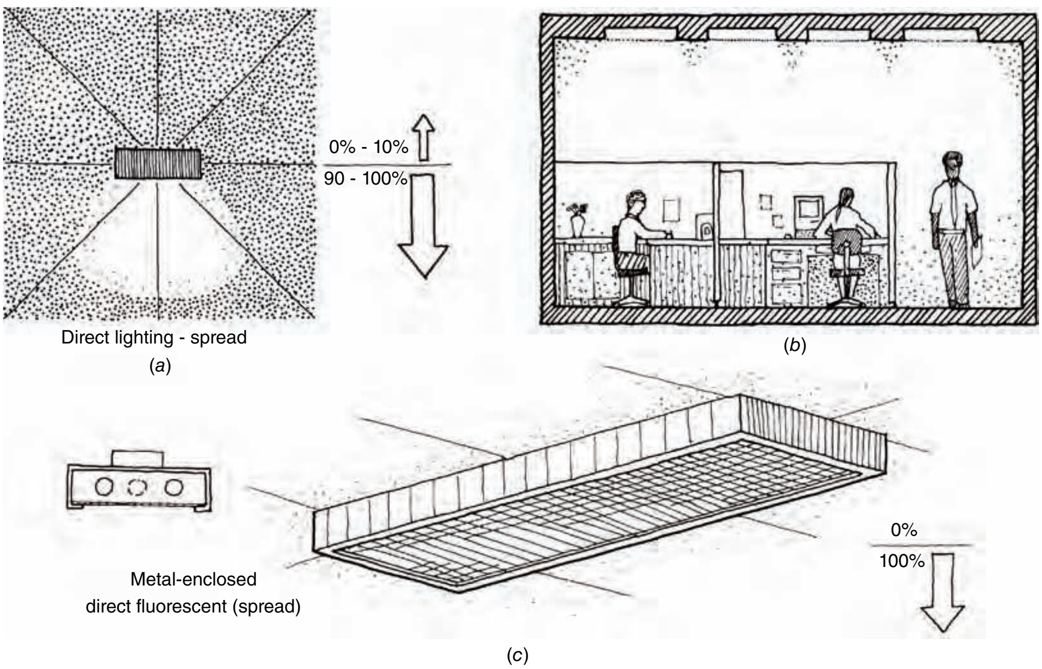


Fig. 15.9 *Spread-type direct lighting (a) illuminates all room surfaces except the ceiling (b), which is only illuminated by reflection from the floor. Some diffuseness is evident. The most common type of unit in this category is the direct fluorescent unit, either troffer-type, recessed in the ceiling (c), or surface-mounted.*

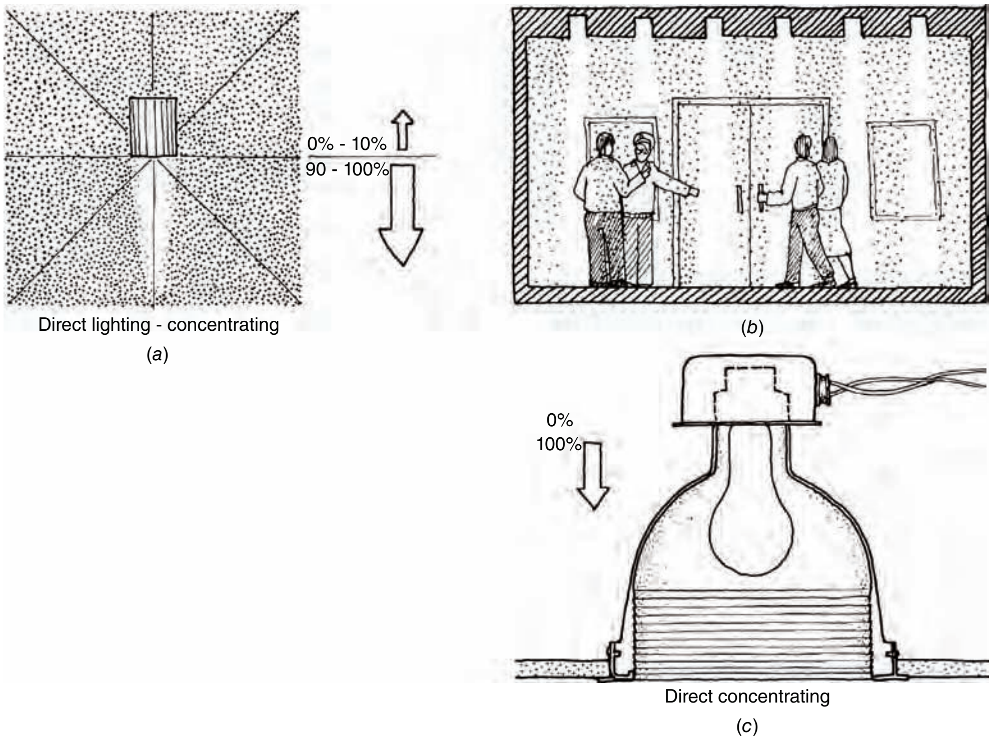


Fig. 15.10 *(a) With concentrated direct distribution, the floor is the only luminous surface (b) other than the ceiling fixture. Diffuseness is absent. Walls are dark. Incandescent downlights (c) and, to a lesser extent, CFL downlights are of this type unless equipped with spread-type lenses.*

from reflections from the floor, furniture, and walls. The result is a working atmosphere with slightly darkened walls and ceiling. This type of lighting, which is most widely represented by a system composed of recessed fluorescent troffers located in a suspended ceiling, is common for general office lighting. The luminaires develop a ceiling surface of light and dark areas, and the quality of the entire system is generally not unpleasant. Although difficulties associated with direct glare and veiling reflections may arise, they can be controlled by the provision of proper luminance ratios, the use of low-brightness fixtures, and the judicious arrangement of viewing positions. When direct lighting units are used in a uniform pattern, this latter option disappears, and the need for particularly low-brightness luminaires and high ceiling reflectivity, or specialty diffusers (such as those with a batwing distribution), is increased.

Direct lighting gives little vertical surface illumination, requiring the addition of perimeter lighting in many space types (Fig. 15.11).

Concentrating downlights create sharp shadows and a theatrical atmosphere that are not appropriate to an office-type commercial space. They can be used in restaurants and other areas where the feeling of privacy, generated by limited-area horizontal illumination and minimal vertical-surface illumination, is desired. When a lighting fixture is designed with a black cone, a baffle, or another device that is nonreflecting at the viewing angle, it appears dark even when lighted. Installations providing high-horizontal surface illumination, with no apparent source of brightness—such as those using black-cone downlights—tend to be disturbing to our normal bright-sun-and-sky orientation, and should be used cautiously and only in limited areas. This

(*a*) (*b*)

Fig. 15.11 *Large-dimension lighting fixtures may be used in a low-ceilinged room if the apparent sizes of the units are reduced. Here at a mounting height of 7.5 ft (2.3 m), 4 ft × 4 ft (1.2 × 1.2-m) units are acceptable because the lattice on the face of each unit gives the impression of reduced fixture size. Note also that the apparent illumination in (b) is greater than in (a) although both are exactly equal on the table surface because of the wall wash in the background. The eye perceives vertical surface illumination more readily than horizontal illumination and retains the impression for the entire space.*

same comment, but to a lesser extent, is applicable to very-low-brightness diffusers such as the parabolic wedge type (see Fig. 16.10). (There, however, the unit has the redeeming characteristic of low reflected glare potential, which is not the case with downlights.) Stated otherwise, the psychological impression of a space without a visible source of light is gloomy and cavelike. When very-low-brightness sources are used, as in areas with lots of computer screens, this negative impression can be alleviated by the addition of luminous surfaces in nonreflecting areas or points of light sparkle.

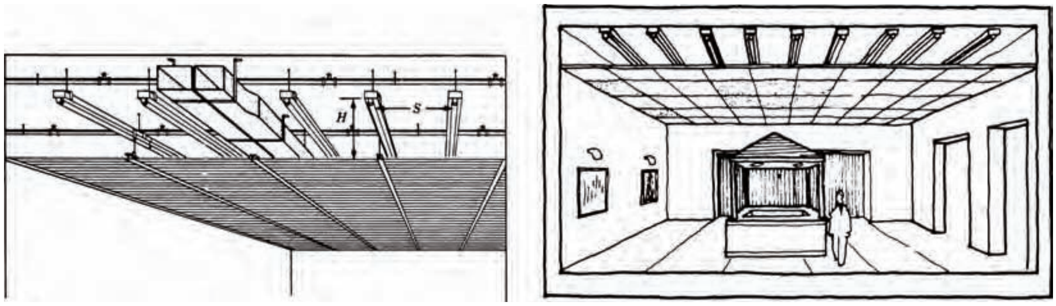
In summary, spread-type direct lighting is suitable for general lighting, whereas concentrated direct lighting (which reduces vertical illumination) is appropriate for highlights, local and supplementary lighting, and specialized privacy-atmosphere installations.

15.16 SIZE AND PATTERN OF LUMINAIRES

Because of its luminance, each luminaire or other luminous source is a point of visual attention. To the extent that luminaires are numerous, large, very bright, or arranged in striking patterns, attention is drawn to them and away from other surfaces. Color elements or accent lighting can also be added deliberately to draw attention. Rigid rules cannot be established to cover these design strategies, but examples can demonstrate the principles involved.

Luminaire size should correlate with room size and ceiling height. Fluorescent fixtures larger than 2 ft × 4 ft (600 mm × 1200 mm) should not be used in ceilings lower than 10 ft (3.1 m) unless the sizes of the fixtures are minimized via the application of a surface pattern (see Fig. 15.11). Transilluminated (luminous) ceilings (Fig. 15.12) require a minimum of 12 ft (3.7 m) mounting height. When they are installed below this level, particularly in large rooms, the effect is oppressive, as if the sky were lowered onto the viewer. To offset this effect, the use of colored, shaped, or dark panels is of some help. In place of a luminous ceiling, large-area, coffer-type fixtures can be utilized in order to give the impression of depth (Fig. 15.13).

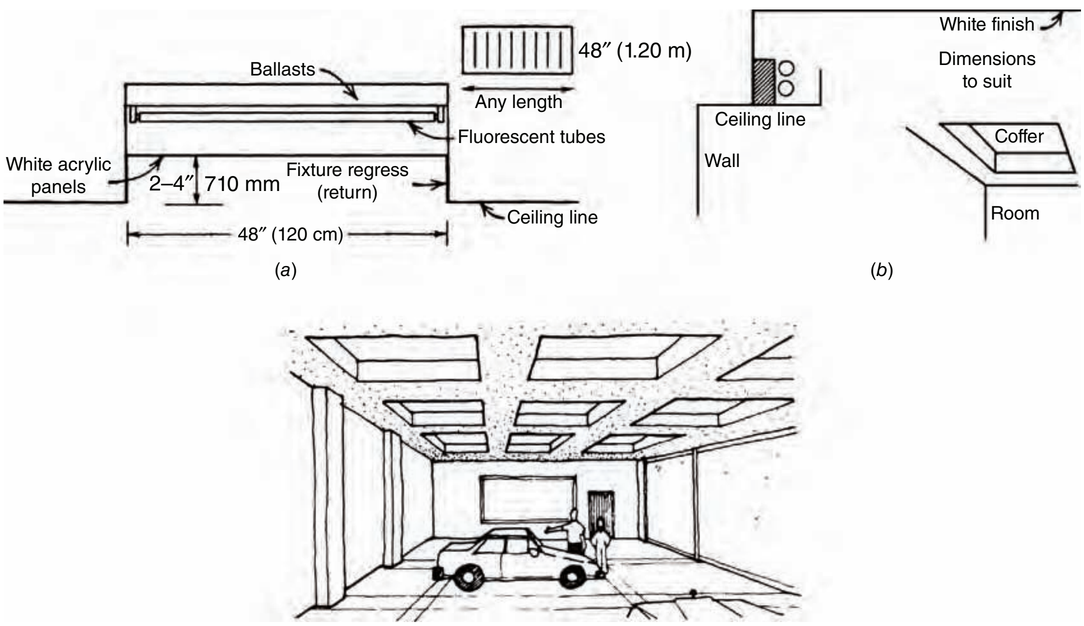
To achieve the uniformity of illumination desirable for general lighting, regular spacing is required. However, various effects may be obtained within said regularity in order to



(*a*) (*b*)

Fig. 15.12 *(a) The suspended diffusive material of a luminous ceiling—when properly designed—allows the designer to hide piping and ductwork, without affecting the ceiling's light distribution. As a rule, if uniform illumination is desired, the spacing (S) of the strip fluorescent fixtures should not exceed 1.5 times the height (H) between the fixtures and the diffusing element. (b) A luminous ceiling provides low-brightness, highly diffuse, uniform illuminance, generally exceeding 500 lux (45 fc). Such a lighting system is particularly useful for specular tasks where supplemental lighting is impractical. To relieve the monotony of large, unbroken expanses, as in (a), designers frequently use clearly defined diffuser panels, as shown.*

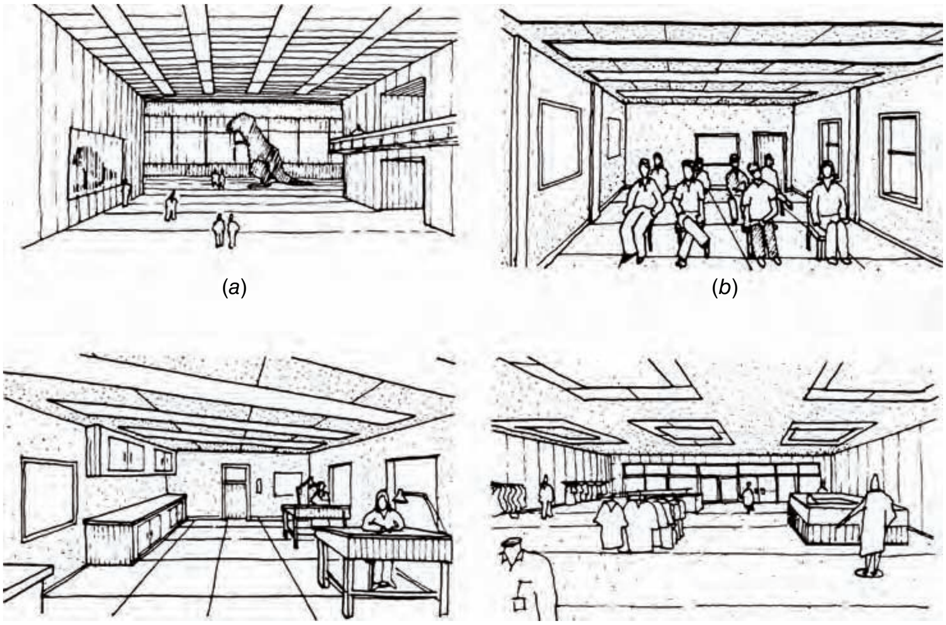
accomplish an architectural purpose, as shown in Fig. 15.14*a–d*. It is often recommended that the pattern of lighting, rather than being at cross-purposes with any dominant architectural pattern—unless this is the desired effect—ought to either reinforce an architectural form or remain neutral. If a strong architectural element is absent, a dominant lighting pattern may be desirable. Conversely, a strong architectural element can either be reinforced (Fig. 15.15*a*) or utilized to carry a neutral lighting pattern (Fig. 15.15*b*, *c*).



(*a*) (*b*)

(*c*)

Fig. 15.13 *Coffer-type light sources come in both standardized (a) or custom-designed (b) sizes. Typical standardized coffers (a) are large direct lighting fixtures that are generally available in 4-ft (1.2-m) widths, and variable lengths. Custom-designed coffers (b) can be constructed in any shape or size. Both types of coffer can give an illusion of great depth and of a floating, illuminated surface. (c) Multiple coffers create a dominant architectural effect, and when designed in conjunction with skylights, can furnish soft, glare-free illumination throughout the day and night.*



(a) (b) (c) (d)

Fig. 15.14 *(a) Longitudinal lines in the direction of the sight line increase apparent length, direct traffic flow, and decrease direct glare. (b) Lines perpendicular to the line of sight shorten and widen a space but also increase direct glare. (c) Diagonal lines minimize shadows and break rectangular patterns. (d) Rectangular pattern is architecturally dominant.*

Continuous-row installations, aside from eliminating the dominant checkerboard effect of closely spaced individual luminaires, are also often cheaper. Coves and cornices give a ceiling a feeling of floating or lightness. Geometric patterns can be used to add interest or to break the monotony of large areas, such as those found in department stores. Generally, downlights are not visually dominant, and regularity of placement is not essential (Fig. 15.16). However, when downlights are surface-mounted (a generally inadvisable procedure), the result can be far from visually neutral (Fig. 15.17). Nonuniform layouts with large fixtures can create a pattern problem since they are often too large to be neutral—the nonuniformity can create visual confusion (Fig. 15.18). The only cure for this problem is to minimize the source brightness by using low-brightness luminaires (see Section 16.4).

In spaces where circulation is the primary "seeing task," but where there are also isolated areas requiring greater illumination (such as waiting areas in transportation terminals), a perimeter lighting system with supplemental lighting can be a viable solution (Fig. 15.19). The MAXXI: Museum of XXI Century Arts, located in Rome, Italy, features elongated slot fixtures that reinforce movement through space and skylights with controllable louvers to illuminate the gallery space (Fig. 15.20). Lighting patterns are often used as formal directional markers. This is particularly useful in transportation terminals, where signs only partially serve this purpose.

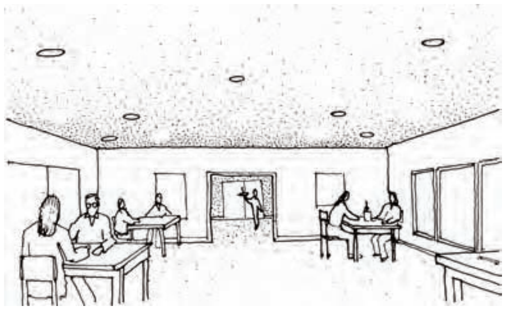
A frequently neglected consideration is the appearance of a luminaire when it is turned off. With proper daylight and energy-conserving design, many fixtures can be turned off during the normal-use hours of a space. Low-brightness sources will change least in appearance. Cognizance of the visibility and appearance of luminaires in daylight, regardless of whether they are illuminated, from inside or outside a building, can be used as an advantage, as shown in Figs. 15.21 and 15.22.

(*a*)

(*b*) (*c*)

Fig. 15.15 *Lighting designs for various spaces with high ceilings. The fixtures in (a) and (b) follow structural beams. (b) Floor reflection and daylight provide ceiling and wall illumination. (c) Lighting in this space was handled by recessing fixtures into the lattice ceiling pattern. Metal–halide HID units and tungsten–halogen units were used. (Photo (a) by M. B. Warren; Photo (b) by L. Reens; Photo (c) courtesy of GTE/Sylvania, Inc.)*

(a)



(b)

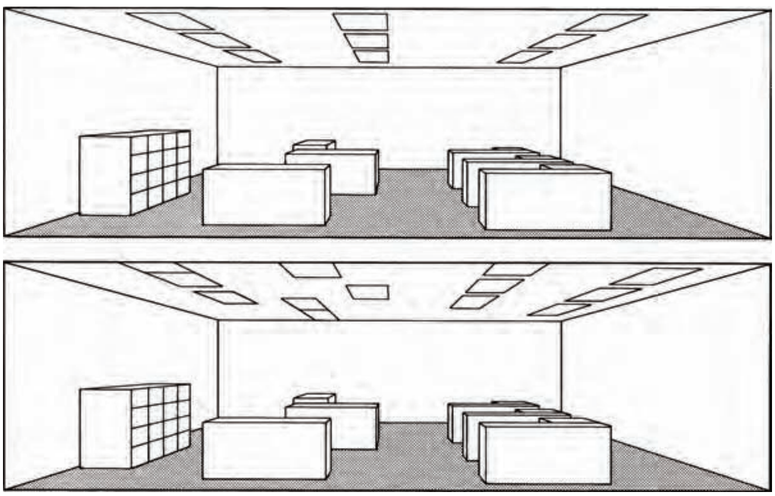
Fig. 15.16 *Downlights are unobtrusive light sources. They can be spaced evenly throughout a room (a) or unevenly (b).*

Fig. 15.17 *The array of large, cylindrical, surface-mounted downlights dominates the area's appearance despite the high ceiling.*

15.17 OTHER DESIGN CONSIDERATIONS

Because the phenomenon of vision, as affected by lighting, is the core of lighting design, it is appropriate to present some miscellaneous, yet important, observations that are not necessarily covered under any of the major headings in this chapter.

1. As shown in Figs. 15.14*a* and 15.14*b*, the impression of room length and width can be emphasized by the direction of lines of lighting. An even wall wash of light can also be used to shorten and widen a hallway or corridor.
2. As seen in Fig. 15.11, the character of a wall, in the line of sight, can affect the room's apparent size. Lighting and low-chroma, high-value



(a)

(b)

Fig. 15.18 *(a) The layout of the lighting fixtures is economical and may provide uniform illuminance. (b) The nonuniform layout lacks integration with the functions below and may not provide the illuminance needed for the task locations.*

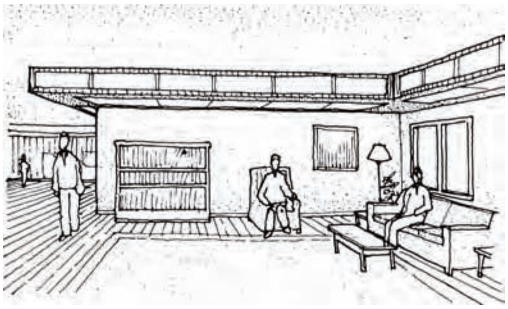


Fig. 15.19 *Cornices, valances, and coves are luminous ceiling borders. In large rooms, suspended coves achieve a uniform ceiling brightness gradient and, when designed with a downward component or combined with supplemental lighting as illustrated, can create a pleasant, intimate atmosphere.*

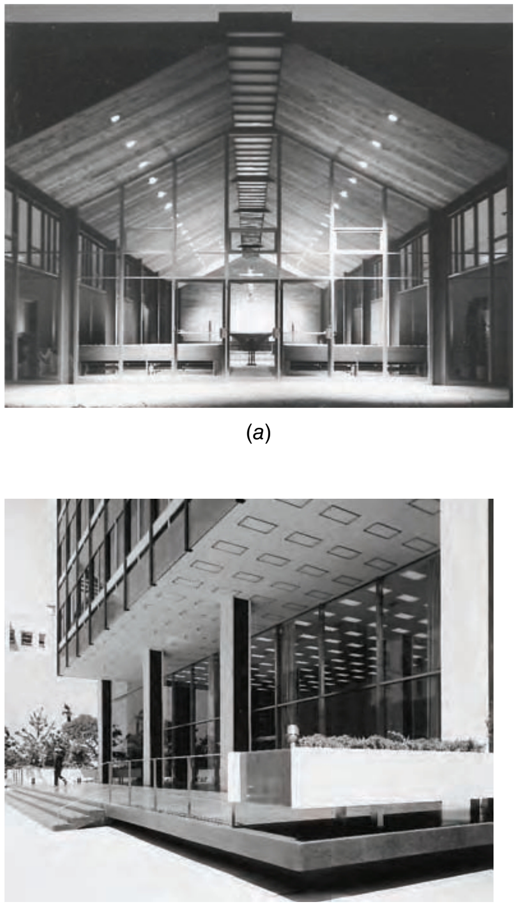
paint hues can be used to expand a space, and conversely, darker-hue paints and a lack of luminance can be used to contract it.

3. Vertical surface illuminance should be approximately 25% to 35% of horizontal illuminance for a space to appear dimensionally undistorted.

Fig. 15.20 *Linear slot lighting emphasizes the curvilinear form of the gallery, further reinforcing a directional flow of traffic through the space. (© Donald Corner; used with permission.)*

Because high luminance attracts the eye, fixtures with sparkle draw the eye away from the walls and thereby shrink the space's horizontal dimensions.

4. As shown in Figs. 15.13*c*, 15.14*c* and *d*, 15.16, and 15.17, luminaire patterns can be dominant (i.e., can become a focus of attention) by virtue of their size or arrangement. The same is true of wall-lighting patterns to an even greater extent, as walls are always in the direct line of sight. Therefore, the lighting designer



(*a*)

(*b*)

Fig. 15.21 *(a) Lighting can be utilized as a medium to connect the inside and outside of a building. The simple maneuver of continuing the lighting pattern beyond the window visually connects the inside and outside spaces. Care must be exercised in order to avoid fixture placement that creates reflections in the glass. (b) Also, as fixtures are readily visible even when unlit during daylight hours, their pattern can be accentuated and the resultant outline continued from the inside to the outside as an architectural motif. (Courtesy of Welton Becket & Assoc.)*

Fig. 15.22 *Electric lighting fixtures can be seen through the glazing even during the daytime. (© Lee Eckert; used with permission.)*

should keep in mind that wall lighting patterns can become dominant visual elements when they create meaningless scallops, spots, irregular gradients, points of sparkle, and so on. In most cases, this is neither intended nor desired. Unscalloped, even-gradient wall illumination is readily accomplished with linear sources, with elliptical reflector lamps, or with luminaire reflectors, if proper luminaire spacing is utilized.

5. Concentrated pools of light, in a space with overall low ambient light, can create isolated pockets of illumination—often perceived as spatially differentiated areas. This can be advantageous in restaurants and work or school areas, where definition of individual “territories” in a single large space is desired.

References and Resources

ASHRAE. 2013. ANSI/ASHRAE/IESNA Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2011. Standard 90.1-2010, *User’s Manual*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. *Advanced Energy Design Guide for Small Office Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA (part of a series of guidelines with various dates).

IESNA. 2011. *The Lighting Handbook*. The Illuminating Engineering Society of North America. New York, NY.

Lightsearch.com—fixtures. www.lightsearch.com/search/fixtures.html

USGBC. 2013. *Leadership in Energy and Environmental Design (LEED)*. U.S. Green Building Council. www.usgbc.org/

CHAPTER 16

Electric Lighting Design

LUMINAIRES

16.1 DESIGN CONSIDERATIONS

(a) General

REFER TO FIG. 15.1 TO SEE THE context for this chapter. At this point in the lighting design process, where design development of the electric lighting system occurs, lighting hardware is chosen based upon considerations brought forth from earlier design stages, and appropriate validation calculations are performed.

Some spaces require overall uniform illumination—these spaces are analyzed by the lumen method, which yields average illuminance. Other spaces utilize local lighting alone, or local lighting to supplement general lighting—requiring point-by-point illuminance calculations or some other method for restricted-area calculation. Additional considerations at this design stage are the control strategy (see Sections 16.13–16.17); type of ceiling system (e.g., modular, movable fixture, and integrated service); and ancillary considerations of ballast noise, luminaire heat distribution, and maintenance. Also decided here is whether to utilize workstation-mounted or built-in lighting, both of which are principally applicable to open-plan spaces.

(b) Luminaire Characteristics

The purpose of a *luminaire* or *lighting fixture* (the terms are synonymous) is twofold: physically, to hold, protect, and electrify the light source; and photometrically, to control the lamp output (i.e., to redirect the light produced) because most common light sources emit light in substantially all directions. The means by which this beam-shaping is accomplished are well known. The characteristics of reflectors, baffles, lenses, and louvers that perform these functions are discussed in some detail in the following sections. However, the problem in luminaire selection is that the requirements are, in many respects, incompatible, and therefore a trade-off between various luminaire characteristics must be made. Thus, for instance, high-efficiency installations can entail high fixture luminance with resultant glare. Desirable wall lighting means high-angle luminaire output with resultant direct glare (see Figs. 13.23 and 13.24). Low-angle light means minimum direct glare but possible veiling reflections. A high shielding angle (>35°) means good visual comfort but reduced efficiency, and so on. It follows that

- No single luminaire design is ideal for even a majority of applications.
- To make an intelligent selection among the hundreds of lighting fixtures commercially available, it is absolutely necessary that the designer understand both the specific requirements of the

application and the light control characteristics of the luminaire being considered.

16.2 LIGHTING FIXTURE DISTRIBUTION CHARACTERISTICS

At this point, review of intensity distribution curves (Section 13.10) by the reader would be useful. The two distribution curves shown in Fig. 16.1*a* are actual test results of two 2-lamp, 1 ft × 4 ft (0.3 m × 1.2 m) semi-direct fluorescent fixtures with prismatic enclosures. The flat bottom of the curve in Fig. 16.1*a* indicates even illumination over a wide area, therefore permitting a high spacing to mounting-height ratio (S/MH) of 1:4, for uniform illumination. The rounded bottom of the curve in Fig. 16.1*b* indicates uneven illumination and closer required spacing for horizontal uniformity as defined in Section 16.5.

The straight sides of the curve in Fig. 16.1*a* show a fairly sharp cutoff, and the small amount of light above 45° means high efficiency, probably insufficient wall lighting, barely adequate diffuseness, and very little direct glare potential but a distinct possibility of veiling reflections. Conversely, the curve in Fig. 16.1*b* shows a large amount of horizontal illumination (above 45°) with resultant direct glare potential, diffuseness, and relative inefficiency, because horizontal light output is attenuated by multiple reflections before reaching the horizontal working plane. Here, however, low output below 45° minimizes reflected glare potential. The uplight component of luminaire (*a*) is directed outward to cover the ceiling and will not cause hot spots; the corresponding light from fixture (*b*) is concentrated above the fixture and gives uneven illumination of the ceiling.

These conclusions were reached based on the following observations:

1. *Uniformity of illumination* requires that the intensity at angles above the nadir (0° from the vertical) be greater than the intensity at 0°, so that location-points distant from the fixture centerline obtain the same illumination as those below the fixture (because illuminance varies inversely with the square of distance). This is exactly the case with the flat-bottom characteristics of Fig. 16.1*a*. Therefore, such fixtures can be spaced more widely than the units of Fig. 16.1*b*.
2. *High efficiency* is achieved by directing the luminaire output to the work plane (i.e., from 0° to 45° from the vertical). Light above 45° is directed to the walls and reaches the working plane only after multiple attenuating interreflections.
3. *Diffuseness* exists when light reaches the work plane from multiple directions. This requires that light be reflected from walls and ceilings to the work plane, which in turn requires luminaire light output above 45° from the vertical.

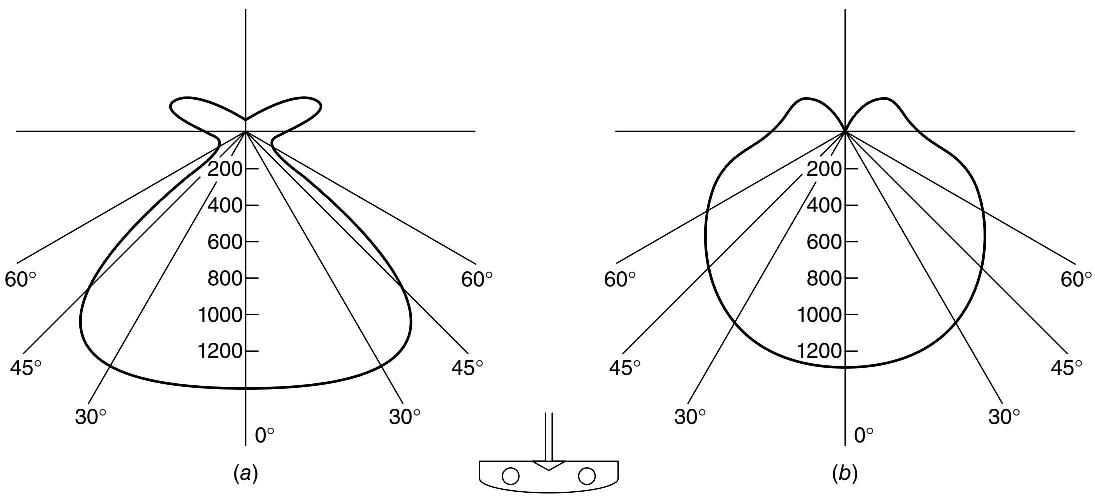


Fig. 16.1 *Semi-direct fluorescent fixture crosswise distribution (two lamps, 32 W each, prismatic enclosure). Note the sharp cutoff and wide, horizontally even distribution of (a) in contrast to the diffuse, broad, and horizontally uneven distribution of (b).*

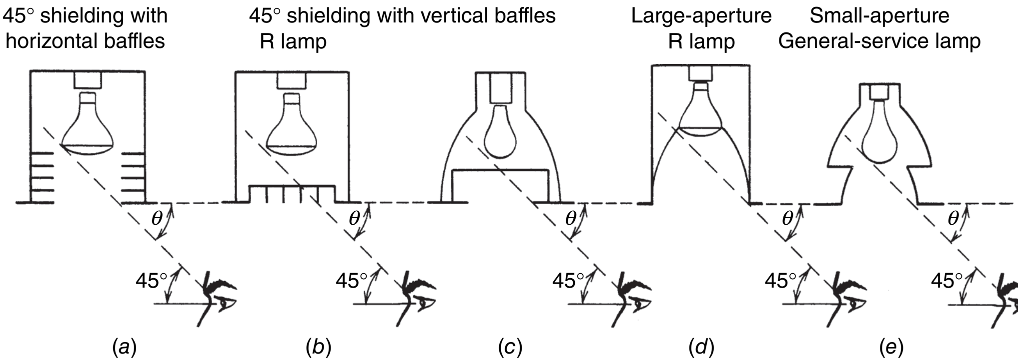


Fig. 16.2 *Methods for shielding downlights using circular shields for vertically symmetrical sources such as incandescent and HID lamps. Halogen lamps mounted vertically in R lamp envelopes are symmetrical; horizontally mounted units in PAR or other reflectors are not. Baffled downlights (a–c) control unwanted high-angle light by cutoff as illustrated. Black baffles aid by absorbing light and appearing dark. Other colors give a ring of light at the baffled edge. Cones (d, e) control brightness by cutoff and by redirection of light due to their shape. They are either parabolic or elliptical. A light specular finish such as aluminum appears dull; a black specular finish appears unlighted. Black finishes require high-quality maintenance because dust shows as a bright reflection. CFL lamps in reflectors are not normally a serious direct glare concern and are considered to be vertically symmetrical. A shielding angle of 45° minimum is recommended for high-luminance lamps.*

4. *Direct glare* is caused by light output at high angles (i.e., above 45° from the vertical). Direct glare from linear fluorescent fixtures can be minimized by placing the long axis parallel to the line of sight, because such fixtures normally have low *endwise* high-angle output.
5. *Reflected glare* is caused by reflection of low-angle output from the task. Therefore, fixtures with control means that limit output between 0° and 45° minimize the potential for veiling reflections (see Section 16.4*b*).
6. *Shielding* is a function of the shape of the fixture housing plus any additional lamp concealment means, such as louvers or baffles. The *shielding angle* is defined as the angle between a horizontal plane through the louvers or baffles and the inclined plane at which the lamp first becomes visible as one approaches the fixture (Figs. 16.2 and 16.3). *Cutoff angle* is usually defined as being synonymous with the shielding angle. However, because some sources define it as the complement of the shielding angle, it is best to avoid the term and use only *shielding angle*.
7. *Ceiling illumination* is produced by light above the horizontal. As with light below the horizontal, a spread-out characteristic (Fig. 16.1*a*) means good ceiling coverage, no hot spots, and, ultimately, good diffuseness. Concentrated

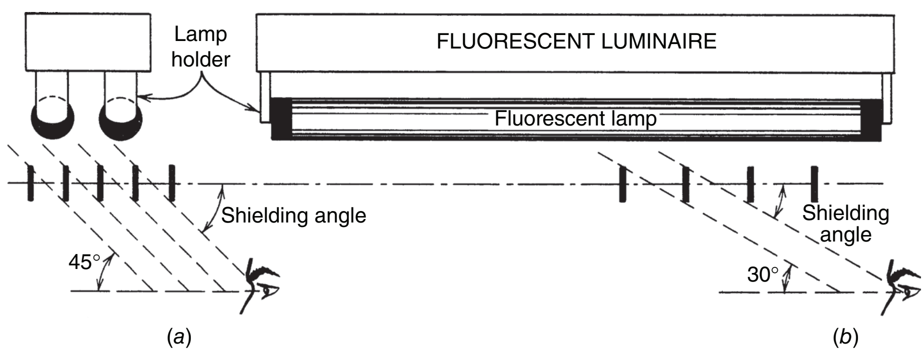


Fig. 16.3 *Shielding of fluorescent lamps is less critical due to lower lamp luminance. For T12 lamps, 45° × 35° crosswise/lengthwise shielding as shown is excellent, and 35° × 30° is satisfactory. For T8 lamps, 45° × 35° should be used. Because fixture luminance is higher in the transverse direction (a) than lengthwise (b), a better cutoff angle is required. The shielding elements may be louvers or baffles. Opaque shielding elements have a higher visual comfort rating than translucent plastic units.*

uplight means a potential hot spot if the fixture suspension hanger is too short, and in any event it yields uneven ceiling illumination.

Thus, we see that a rapid inspection of a fixture curve can yield a large amount of information on the fixture's performance. The reader is encouraged at this juncture to review the comments on the two distribution curves of Fig. 16.1 and then analyze similarly other distribution curves in manufacturers' catalogs.

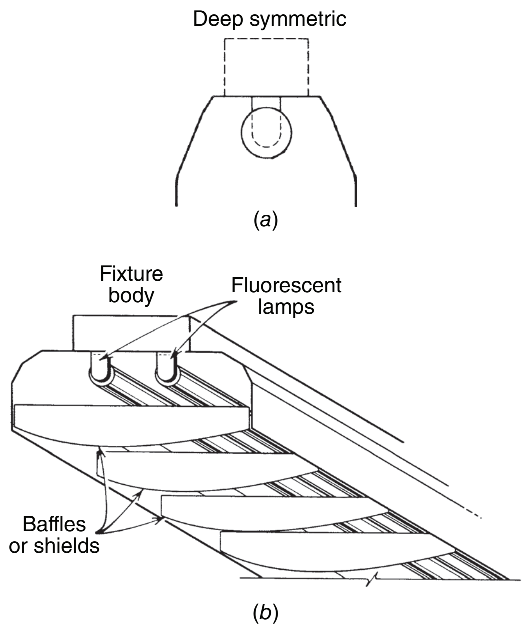
16.3 LUMINAIRE LIGHT CONTROL

(a) Lamp Shielding

Except where it is desired to use a bare lamp as a source of sparkle, such as in chandeliers and other decorative fixtures, all lamps in interior fixtures should be shielded from normal sight lines (i.e., sight lines in a head-up, eyes-straight-ahead position; see Fig. 13.19). The reason is simple; bare lamps are so bright (see Table 13.2) that they usually constitute a source of direct or even disabling glare, depending on the apprehended angle (closeness to the eye and size of the lamp) and eye adaptation level. The range of permissible luminaire luminances (listed in Table 13.3) of 1000 to 7000 cd/m^2 depends upon these two variables (apprehended angle and adaptation level).

As a general rule, exposed incandescent lamps, 6 W and larger, are sources of direct glare and should be avoided. Note that the upper direct-glare limit corresponds to the luminance of a bare 34-W T12 fluorescent tube, which accounts for the fact that bare-lamp fluorescent fixtures are well tolerated. However, when such a fixture is relamped (and reballasted) with a more efficient, better CRI, T8 lamp whose luminance exceeds 10,000 cd/m^2, it becomes a source of annoying direct glare that actively impairs visual ability.

Shielding of lamps is accomplished with the fixture housing/reflector or with baffles and louvers, as mentioned previously (see Figs. 16.2, 16.3, and 16.4). Fluorescent fixtures require shielding most when placed crosswise to the line of sight, thus exposing the entire length of the lamp to the field of view. Such fixtures require longitudinal baffles, deep housings, or louvers to provide the necessary shielding. Alternatively, when at all possible, place fixtures with their long axis in the direction of sight lines.



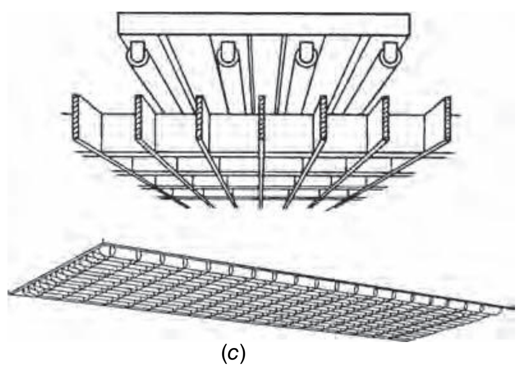


Fig. 16.4 *Shielding elements. (a) The most basic shielding element is the lamp reflector, which may double as the fixture body. (b) Shields perpendicular to the long axis of a linear fluorescent lamp are normally called baffles. They are less important than lengthwise shields (louvers) because endwise lamp luminance is lower than crosswise luminance. (c) Two-way shielding is most effective but seriously lessens luminaire efficiency. (From B. Stein. 1997.* Building Technology: Mechanical and Electrical Systems*, 2nd ed.; reproduced by permission of John Wiley & Sons.)*

(b) Reflectors

It is important to understand the action of luminaire reflectors. The basic shapes and beam patterns are illustrated in Figs. 16.5 through 16.7. Note from Fig. 16.6 that the so-called pinhole downlight requires an elliptic reflector to focus the light through this hole at point *f2* in order to maintain even minimal fixture efficiency. Elliptic reflectors are large, and frequently the space above the ceiling is too restricted for their use. Lamps with integral elliptic reflectors can be utilized with a standard baffled reflector to achieve roughly the same effect.

(c) Reflector Materials

Until fairly recently, reflector materials were of two types: white gloss paint for portions of fixture body interiors that acted as reflectors, and formed anodized aluminum sheet for the shaped reflectors of the types shown in Figs. 16.5 through 16.7. The reflectances (reflection factors) of both of these materials are approximately the same, varying between 0.84 and 0.88 *when new and clean*. Neither, however, is truly specular; the paint finish is actually primarily diffuse, whereas the aluminum is principally specular. Where shaped reflectors are not used, as in the case of a fluorescent troffer, the lack of specularity is essentially immaterial because, at worst, the diffuseness will reduce luminaire output slightly by increasing the number of interreflections within the fixture body (Fig. 16.8*a*). The idealized specular reflections for shaped reflectors shown in Figs. 16.5 through 16.7 are just that; in reality, the reflectances are considerably more diffuse and become increasingly so with reflector aging and dirt accumulation.

Painted fixture body interiors lose their high reflectance by rapid aging due to elevated temperatures and accumulation of dust and dirt. This causes a decrease in overall reflectance, which is

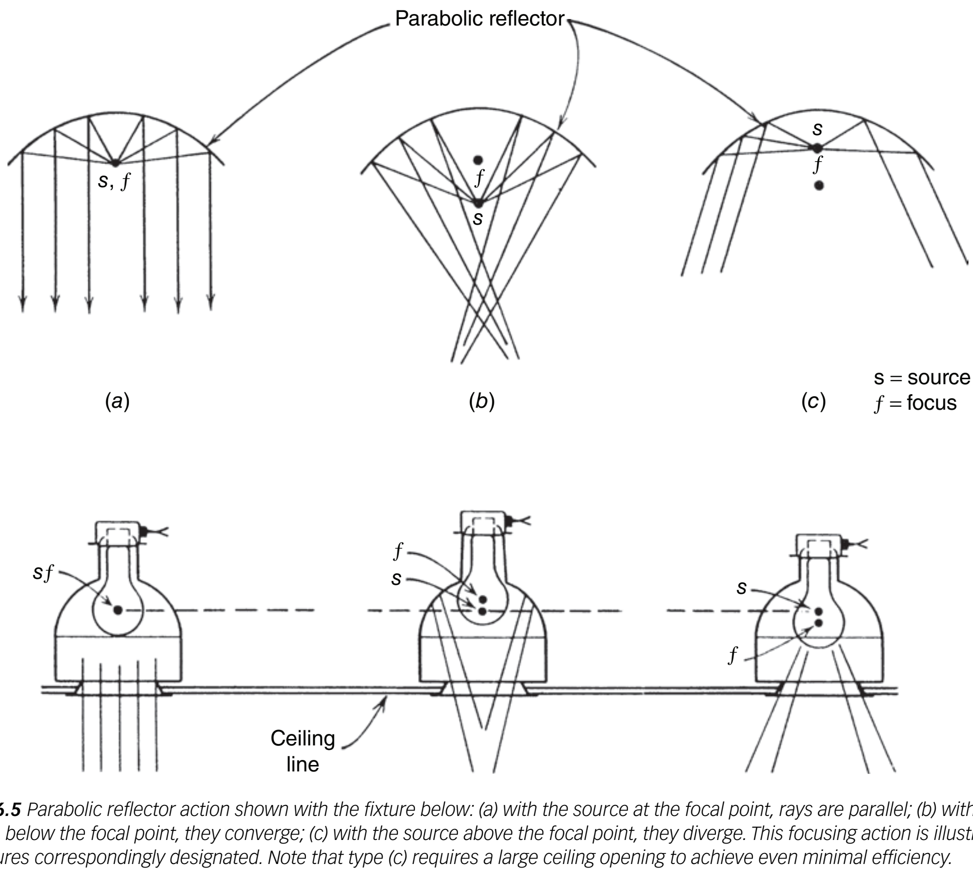
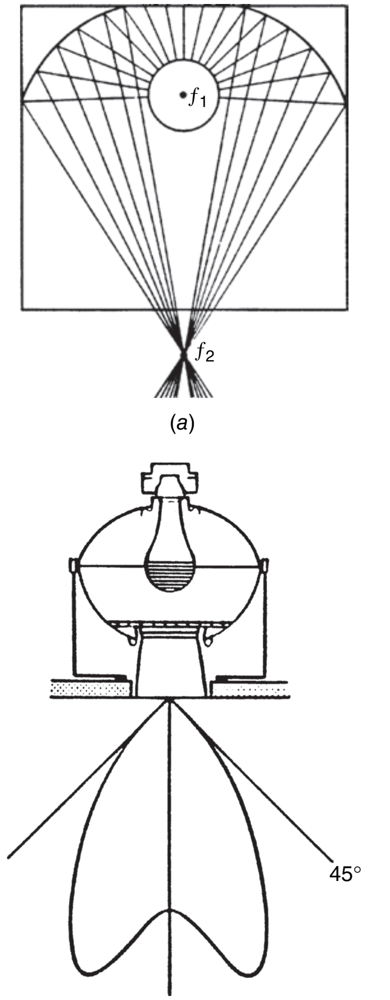


Fig. 16.5 *Parabolic reflector action shown with the fixture below: (a) with the source at the focal point, rays are parallel; (b) with the source below the focal point, they converge; (c) with the source above the focal point, they diverge. This focusing action is illustrated by fixtures correspondingly designated. Note that type (c) requires a large ceiling opening to achieve even minimal efficiency.*



(b)

Fig. 16.6 *(a) Action of an elliptical reflector section. With the light source at focal point* f_1 *the light converges at the other focal point,* f_2. *This effect is useful in fixture design, as in (b). By projecting light up only (through the use of a silvered bowl lamp), the output light can be redirected through a constricted aperture at the other focal point, with little loss. This design is the basis of high-efficiency "pinhole" downlights.*

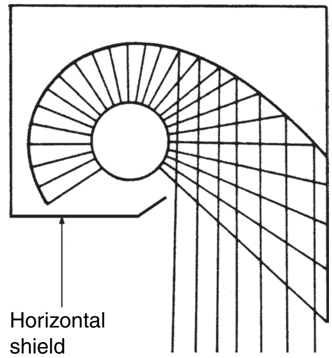


Fig. 16.7 *The extended section reflector allows the source to be concealed (shielded) while projecting its light directly down, but horizontally displaced, from the source.*

compensated for by initial overdesign, as explained in Section 16.20. However, because a rectangular fixture body is not an accurately shaped reflector, the result of overall reflectance reduction is simply an overall reduction in output while maintaining the same photometric *distribution* characteristics.

Energy conservation programs and utility rebates (now generally terminated) led to the introduction via retrofits of very-high-reflectance auxiliary reflectors that were added to existing fluorescent troffers approximately as shown in Fig. 16.8*b*. Unfortunately, many of the claims of highly increased efficiency were based on retrofitting aged, dirty luminaires, and their results were often very misleading. A reasonable estimate of the possible improvement in luminaire efficiency can be made by considering these facts:

- Approximately 40% of a lamp's output in an open luminaire is directed downward and is therefore completely independent of any reflector action.
- The difference in reflectance between a new, clean, painted surface and an old, dirty surface is, *at most*, 50%. That means that the *maximum* light loss of an open fixture due to poor maintenance is 50% of 60% (the latter percentage being the maximum reflected light component), or 30% of the overall light output. Reference is always to an open-bottom fixture.
- The maximum reflectance of the best (and most expensive) silver reflectors is about 95%, comprising 93% specular and 2% diffuse. This is only 10% higher than the original *minimum* 85% paint reflectance. Therefore, at most, retrofit of a very dirty, old fixture with a high-quality (expensive) silver reflector improves performance by the 30% lost to dirt plus 10% of the 60% reflected light for a total of 36% *maximum*. Relamping, of course, also improves output, but that is not connected with fixture body reflectance.
- Simple cleaning of a very dirty fixture body restores 20% to 25% of the light loss. The

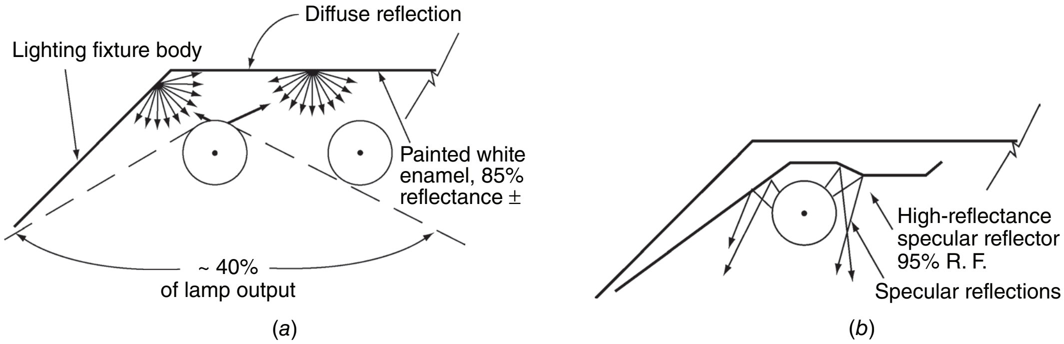


Fig. 16.8 (a) Approximately 40% of lamp output in an open linear fluorescent fixture is unrestricted. The remainder leaves the fixture after one or more reflections. (b) A mirrored reflector narrows the distribution pattern of the luminaire by specular reflection and increases output somewhat (R.F. is reflectance factor).

remaining loss is due to aging of the paint. A cost analysis is required to determine whether the 10% to 15% differential in light output between simple cleaning and silvered reflector addition is economically feasible.

An important consideration in retrofit and new construction is the photometric characteristic of high-reflectance linear fluorescent luminaires. In general, they are shaped like the curve of Fig. 16.1*b*. This means, as explained in Section 15.16, that light is concentrated downward, resulting in a requirement for closer luminaire spacing to obtain uniform illumination. In new construction, this can be considered in design, although it can be a serious economic penalty. In retrofit work, it can result in unacceptable lack of illuminance uniformity, requiring additional luminaires and expensive relocation of existing units.

Another factor to be considered is the degree of maintenance required to keep "super" reflectors in pristine condition in order to achieve the 15% ± maximum output differential. To determine this, designers should request an aging test and inspect a previously retrofitted installation with ambient conditions and cleaning schedules similar to those of the area under consideration.

16.4 LUMINAIRE DIFFUSERS

Diffusers are the devices placed between the lamp(s) and the illuminated space, that function to diffuse the light, control fixture brightness, redirect the light, and obscure (hide) and shield the lamps. Because most of these devices perform multiple functions, they are discussed individually.

(a) Translucent Diffusers

Because these do not redirect the light but merely diffuse it, the distribution characteristic is circular, as seen in Fig. 16.9*a*. Typical examples of this type are white opal glass, frosted glass, and white plastics such as Plexiglas, polystyrene, vinyl, and polycarbonates. The distribution is basically the same as it would be for bare lamps: lamp-hiding power is good; depending on the material, direct glare can be a problem; visual comfort probability (VCP) is poor; veiling reflections are high; the S/MH does not exceed 1.5; the fixture is generally inefficient; and wall illumination is good because of a large component of high-angle light (which reduces VCP). The net result of using this type of diffuser is a reduction in lamp luminance due to a distribution of the lamp output over a larger diffusing area. Applications include corridors, stairwells, high-ceilinged spaces, and other areas without demanding visual tasks.

A special type of flat plastic panel that polarizes the transmitted light, when initially introduced, held great promise because it produces a marked decrease of veiling reflection at an angle of 60°, but much less at other angles. Because most viewing is in the range 20° to 40°, using these panels did not result in any appreciable reduction in reflected glare in normal office work situations. From experience in a drafting room equipped with luminaires utilizing high-efficiency multilayer polarizers, it can be

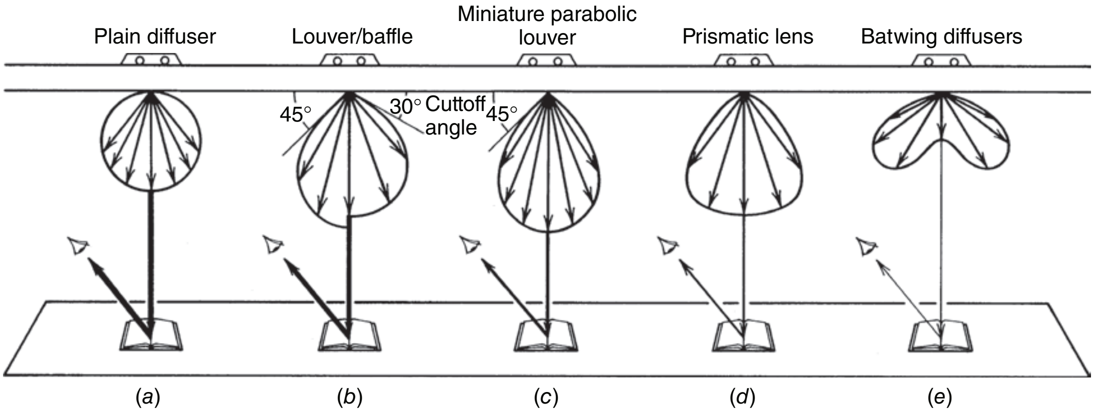


Fig. 16.9 *Comparison of typical candlepower distribution curves for common linear or PL lamp fluorescent luminaire diffuser elements (for a full description of types a–d, see text). Note that for a given geometry of viewer and luminaire, the severity of veiling reflections depends entirely on the fixture's photometric characteristic. In the individual figures, the potential to produce reflected glare is indicated by the weight of the line representing fixture output and reflectance from the work task. The batwing distribution (e) concentrates its output in the 30° to 60° range, which minimizes both direct and reflected glare.*

stated that visual discomfort from reflected glare, as personally experienced and as reported by a large staff, was not noticeably reduced.

(b) Louvers and Baffles

These are generally rectangular in shape, and are composed of metal or plastic; they serve primarily to shield the source (see Figs. 16.2 and 16.3) and to diffuse the output, particularly when plastic translucent louvers are used. Candlepower distribution curves are shown in Fig. 16.9*b*. The exact curve shape depends on the shielding angle, design of the louver, and its finish. Louvers finished in specular aluminum or dark colors exhibit low direct glare. The large downward light component can cause serious veiling reflections. Overall fixture efficiency is average.

The S/MH, a luminaire metric that indicates the maximum spacing permissible for a given luminaire mounting height that yields uniform illumination and is given as a dimensionless ratio, is fully explained in the next section. For this diffuser type, it does not exceed 1.5 and varies inversely with the shielding angle. This is because the basic circular distribution is changed to an egg shape by cutoff and redirection, reducing the high-angle light. Thus, a 45° shielding angle results in lower direct-glare potential but requires closer spacing.

A special design in this category is the miniature eggcrate parabolic wedge louver shown in Fig. 16.10. These units redirect a large portion of the light directly downward, and because of this redirection and their specular finish, they appear completely dark—darker, indeed, than the unlighted portion of the ceiling when viewed obliquely. Fixtures using these louvers have low efficiency due to trapped light, with a maximum coefficient of utilization of about 0.5 (see Section 16.21). VCP is very high, but veiling reflections can be troublesome; S/MH varies between 1.0 and 1.5. The shielding angle is usually 45°. A typical candlepower distribution curve is shown in Fig. 16.9*c*. When these units are used, additional wall lighting is almost always required. The luminance of fixtures and surfaces can be easily checked in the field using a portable luminance meter, as in Fig. 16.11

Because of the low efficiency of the parabolic louver design shown in Fig. 16.10*a*, caused by the wide light-trapping tops of the louvers, an improved version was developed with the tops shaped to reflect incident light efficiently. This improved design, which is shown in Fig. 16.10*b*, increases luminaire efficiency by about 20%.

(c) Prismatic Lens

Many designs are available with varying distribution characteristics. Figures 16.1*a* and 16.9*d* can be taken as typical of this genre. They produce an efficient fixture (high coefficient of utilization), good diffusion, wide permissible spacing—an S/MH as high as 2.0—and low direct glare (high VCP).

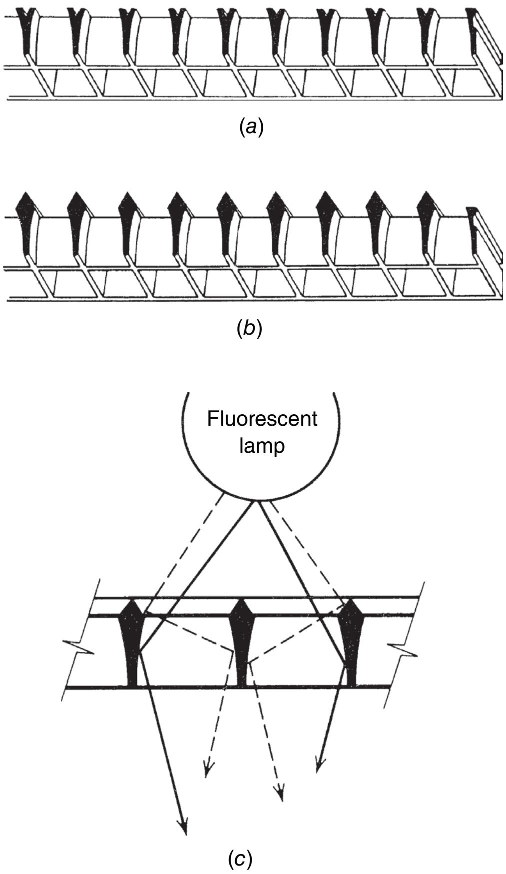


Fig. 16.10 (a) Section through a conventional, miniature parabolic wedge, eggcrate type of louver. These units give exceptionally low brightness when seen at a normal viewing angle. Most such units are made of aluminized plastic. Fixtures equipped with these units exhibit low overall efficiency due to the large amount of light trapped by the broad top of each parabolic wedge. (b) A modified wedge design uses a curved top on each wedge to redirect and utilize light striking the top. (c) Solid lines represent light rays redirected by the bottom curve, whereas dotted lines show light redirected by the top curve, which was lost in the design of (a). Typical louver cell dimensions are a ½-in. (12-mm) cube for design (a), with a consequent 45° shielding angle, and ⁵⁄₆ to ¾ in. (21 to 19 mm) square by ½ in. (12 mm) high for design (b), giving a 35° to 45° shielding angle.

Veiling reflections can be troublesome, depending upon viewing angles and position (see Fig. 13.32).

(d) Fresnel Lens

The action of this lens is similar to that of a reflector: lamp-hiding power is poor, but efficiency is high and visual comfort is good; S/MH is seldom more than 1.5 (Fig. 16.12).

Fig. 16.11 Checking the luminance of a fluorescent fixture with a luminance meter.

(e) Batwing Diffusers

The theory behind this type of diffuser is covered in Section 13.31*c*. A typical characteristic is shown in Fig. 16.9*e*. There are two fluorescent luminaire designs that produce the batwing shape distribution characteristic—a prismatic lens and parabolic reflectors and baffles.

1. *Prismatic batwing diffusers.* These are either linear or radial; that is, they produce the batwing

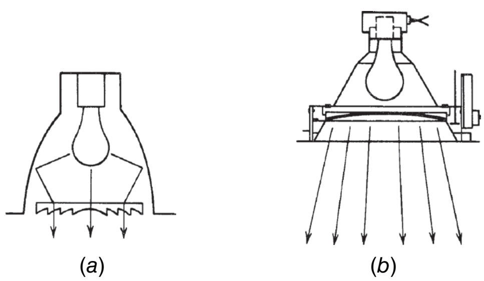


Fig. 16.12 Action of a Fresnel lens. With a Fresnel lens fixture, a smaller housing without a reflector can be used while still maintaining beam control. The lens performs the same function as a reflector, controlling the beam as a function of source placement. By utilizing a lens fixture, the curved reflector (a) can be largely eliminated, yielding a smaller fixture while maintaining accurate beam control. A common design (b) uses a regressed lens to provide shielding, although lens brightness is not normally objectionable.

distribution either in one direction or in all directions. Typical characteristics of both types are shown in Fig. 16.13. Note that the characteristic shape is more pronounced in the linear diffuser, which indicates better control of veiling reflections in that direction (usually crosswise). Fixtures equipped with these diffusers have good efficiency, low direct and reflected glare, and good diffusion. As with all enclosed ungasketed fixtures, the lens acts as a dust trap, necessitating frequent cleaning to maintain high output.

2. *Deep parabolic reflectors.* These luminaires (Fig. 16.14) produce modified versions of the characteristic batwing distribution in the normal (crosswise) direction. Distribution in the parallel or lengthwise direction is circular (diffuse), indicating minimum beam control in that direction. These fixtures, like the batwing lens-type diffuser units, have high efficiency, high S/MH, low reflected glare, and low to very low surface brightness, making them usable in digital display areas. They are normally applied with the long axis in the direction of sight lines.

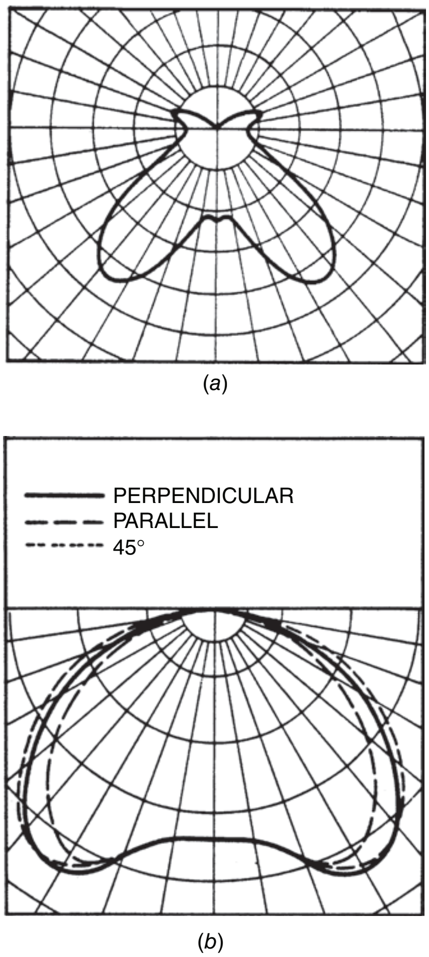
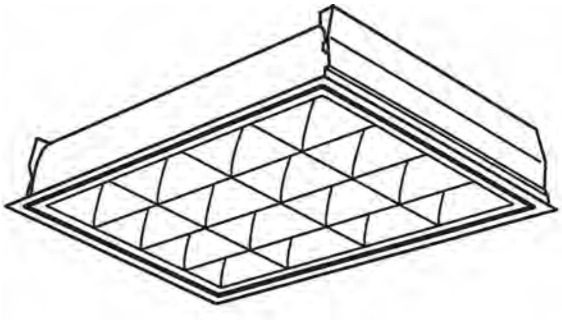


Fig. 16.13 *(a) Linear batwing distribution with extremely sharp cutoff in the upper and lower ranges. The curve is taken across the lamp axis for a single-lamp unit. (b) Distribution curves for a radial batwing distribution lens. Note that the perpendicular, parallel, and diagonal curves are almost identical. Zonal flux is maximum in the 30° to 60° range and drops off at both extremes, as desired.*

16.5 UNIFORMITY OF ILLUMINATION

In any space intended to be lighted uniformly with multiple, discrete, ceiling-mounted direct-lighting system light sources, it is necessary to establish a fixture spacing that gives acceptable uniformity of illumination. A ratio of maximum to minimum illuminance on the working plane of 1:1.3 is readily acceptable because lesser ratios are not easily noticed. For general background or circulation lighting, a ratio of up to 1.5 is acceptable. The S/MH recommendations given by manufacturers (see the figures immediately above the distribution curves for each fixture in Table 16.1) are generally based upon a 1.0 illuminance ratio (Fig. 16.15). Therefore, the S/MH recommendation may be exceeded somewhat without affecting uniformity.

When the luminaire's distribution characteristic is symmetrical in all directions, as is generally the case with small-source lamps such as incandescent, compact fluorescent (CFL), and high-intensity discharge (HID), only a single S/MH figure is required. However, with the asymmetrical distribution of most fluorescent fixtures, an S/MH ratio is required both crosswise and lengthwise. Due to the characteristic of the lamp itself, the transverse (crosswise, perpendicular) ratio is almost always considerably higher than the longitudinal (parallel, endwise, lengthwise) ratio. See, for instance, fixtures 26, 28, and 42 in Table 16.1. The S/MH (also called *spacing criteria* [SC]) for a specific luminaire is determined by measuring the distance between two test luminaires that yields the same illuminance on the working plane midway between them as directly

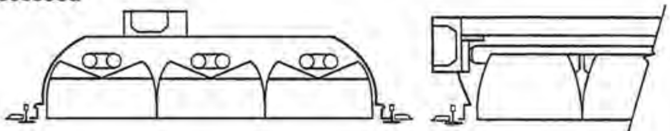


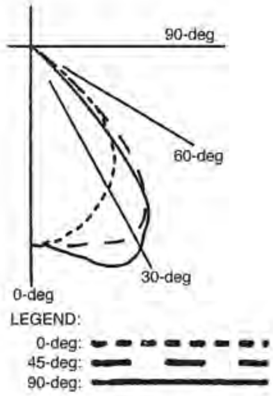
TOTAL LUMINAIRE EFFICIENCY	=	66.0 %	
TOTAL REFLECTANCE OF PAINT	=	88.3 %	
CIE TYPE – DIRECT			
PLANE	:	0-DEG	90-DEG
SPACING CRITERIA	:	1.2	1.6
SHIELDING ANGLES	:	36	43
PLANE	:	0-DEG	90-DEG
LUMINOUS LENGTH	:	21.250	21.250

LUMINANCE DATA IN FOOTLAMBERTS

ANGLE IN DEG	AVERAGE 0-DEG	AVERAGE 45-DEG	AVERAGE 90-DEG
45	2451.	3101.	1927.
55	494.	639.	55.
65	0.	0.	0.
75	0.	0.	0.
85	0.	0.	0.

Recessed





Visual Comfort Probability

Reflectance - 80, 50, 20
Work Plane Illumination - 100 FC@ 2.5 ft.

VCP

Room W	Room L	Ht.	Luminaires Lengthwise 8.5	Luminaires Lengthwise 10.0	Luminaires Lengthwise 13.0	Ht.	Luminaires Crosswise 8.5	Luminaires Crosswise 10.0	Luminaires Crosswise 13.0
20	20		68	81	77		90	90	87
20	40		69	81	77		91	90	84
30	30		69	81	77		91	90	84
30	60		69	82	78		91	90	84
40	40		69	82	78		91	90	84
40	60		70	82	78		91	90	84
60	30		69	82	78		91	90	84
60	40		70	82	78		91	90	84
60	60		70	82	78		91	91	84

Coefficients of Utilization

Coefficients of Utilization
Zonal Cavity Method — Floor Reflectance - .20

RC	80				50		
RW	70	50	30	10	50	30	10
1	75	73	71	69	69	67	66
2	71	67	65	62	64	62	60
3	67	62	59	56	59	57	54
4	63	57	54	50	55	52	50
5	59	53	49	46	51	48	45
6	55	49	44	41	47	43	41
7	51	44	40	37	43	39	36
8	48	41	36	33	39	35	33
9	44	37	32	29	36	32	29
10	41	34	29	26	33	29	26

Energy Data

LER: FP-42 — **Energy Cost: $5.71****
Input Watts: 134 — **BF: .90**

The above energy calculations were conducted using a specific lamp/ballast combination. Actual results may vary depending upon the lamp and ballast used. Lamp and ballast specifications are subject to change without notice.

*Comparative annual lighting energy cost per 1000 lumens based on 3000 hours and $0.08 per KWH.

Fig. 16.14 *A 2-ft (610-mm) square, deep parabolic reflector luminaire designed for three F40, 22.5-in (572-mm) twin-tube CFL lamps, with a rated output of 3150 lm each. Total power input is 134 W and ballast factor (BF) is 0.9, giving a luminaire efficacy rating (LER) of 42. The typical modified batwing crosswise distribution and circular lengthwise distribution are clearly shown. Photometric data of interest to lighting designers are also shown. (Courtesy of Columbia Lighting.)*

TABLE 16.1 Coefficients of Utilization for Typical Luminaires with Suggested Maximum Spacing Ratios

To obtain a coefficient of utilization (CU):

1. Determine the cavity ratios for the room, ceiling, and floor.
2. Determine the effective ceiling and floor cavity reflectances from Table 16.2. Use initial ceiling, floor, and wall reflectances.
3. Obtain the CU for a 20% effective floor cavity reflectance from the appropriate column for the luminaire type to be used. Interpolate, when necessary, to obtain the CU for the exact room cavity ratio for the nearest effective ceiling cavity reflectances above and below the reflectance obtained in step 2; interpolate between these CUs to obtain the CU for the step 2 ceiling cavity reflectance.
4. If the effective floor cavity reflectance differs significantly from 20%, obtain the multiplier from Table 16.3 and apply this to the CU obtained in step 3.
5. To obtain the CU for a ceiling cavity reflectance (ρ_{CC}) of 30 or 10%, multiply the figure for ρ_{CC} = 50% by 0.85 or 0.70, respectively. This is an approximation. For exact figures, see the IESNA Lighting Handbook (2000).
6. Use the figure in the last column (ρ_{CC} = 0; ρ_w = 0) for outdoor lighting, i.e., there are no walls or ceiling.
7. Legend:

ρ_{CC} = percent effective ceiling cavity reflectance

ρ_w = percent wall reflectance

RCR = room cavity ratio

Maximum S/MH guide = ratio of maximum luminaire spacing to mounting above work plane

Note: In some cases, luminaire data in this table are based on an actual typical luminaire; in other cases, the data represent a composite of generic luminaire types. Therefore, whenever possible, specific luminaire data should be used in preference to this table.

The polar intensity sketch (candlepower distribution curve) and the corresponding spacing-to-mounting height guide are representative of many luminaires of each type shown.

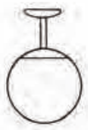
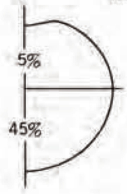
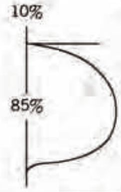
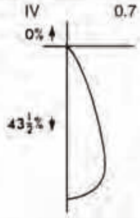
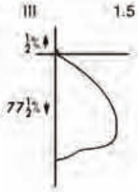
	Typical Distribution and Percent Lamp Lumens		ρ_{CC}: →	80			70			50			0
			ρ_w: →	50	30	10	50	30	10	50	30	10	0
Typical Luminaire	*Maintenance Category*	*Maximum S/MH*	*RCR*	*Coefficients of Utilization for 20% Effective Floor Cavity Reflectance (ρ_{FC} = 20)*									
1  Pendant diffusing sphere with incandescent lamp	V	1.5	0	.87	.87	.87	.81	.81	.81	.69	.69	.69	.44
			1	.71	.67	.63	.66	.62	.59	.56	.53	.50	.31
			2	.61	.54	.49	.56	.50	.46	.47	.43	.39	.23
			3	.52	.45	.39	.48	.42	.37	.41	.36	.31	.18
			4	.46	.38	.33	.42	.36	.30	.36	.30	.26	.15
			5	.40	.33	.27	.37	.30	.25	.32	.26	.22	.12
			6	.36	.28	.23	.33	.26	.21	.28	.23	.19	.10
			7	.32	.25	.20	.29	.23	.18	.25	.20	.16	.09
			8	.29	.22	.17	.27	.20	.16	.23	.17	.14	.07
			9	.26	.19	.15	.24	.18	.14	.20	.15	.12	.06
3  Porcelain-enameled ventilated standard dome with incandescent lamp	IV	1.3	0	.99	.99	.99	.97	.97	.97	.92	.93	.93	.83
			1	.88	.85	.82	.86	.83	.81	.83	.80	.78	.72
			2	.78	.73	.68	.76	.72	.67	.73	.69	.66	.61
			3	.69	.62	.57	.67	.61	.57	.65	.60	.56	.52
			4	.61	.54	.49	.60	.53	.48	.58	.52	.48	.45
			5	.54	.47	.41	.53	.46	.41	.51	.45	.41	.38
			6	.48	.41	.35	.47	.40	.35	.46	.39	.35	.32
			7	.43	.35	.30	.42	.35	.30	.41	.34	.30	.28
			8	.38	.31	.26	.38	.31	.26	.37	.30	.26	.24
			9	.35	.28	.23	.34	.27	.23	.33	.27	.23	.21
7  EAR-38 lamp above 51-mm (2 in.)-diameter aperture (increase efficiency to 54½% for 76-mm (3 in.)-diameter aperture)	IV	0.7	0	.52	.52	.52	.51	.51	.51	.48	.48	.48	.44
			1	.49	.48	.48	.48	.48	.47	.47	.46	.46	.42
			2	.47	.46	.45	.46	.45	.44	.45	.44	.43	.41
			3	.45	.44	.43	.45	.43	.42	.44	.42	.42	.40
			4	.43	.42	.41	.43	.41	.40	.42	.41	.40	.38
			5	.42	.40	.39	.41	.40	.38	.41	.39	.38	.37
			6	.40	.39	.37	.40	.38	.37	.39	.38	.37	.36
			7	.39	.37	.36	.39	.37	.36	.38	.37	.35	.35
			8	.37	.36	.34	.37	.35	.34	.37	.35	.34	.33
			9	.36	.34	.33	.36	.34	.33	.35	.34	.33	.32
18  "High-bay" wide distribution ventilated reflector with clear HID lamp	III	1.5	0	.93	.93	.93	.91	.91	.91	.87	.87	.87	.78
			1	.85	.82	.80	.83	.81	.79	.79	.78	.76	.70
			2	.77	.73	.70	.76	.72	.69	.73	.70	.67	.63
			3	.70	.65	.61	.68	.64	.60	.66	.62	.59	.56
			4	.63	.58	.53	.62	.57	.53	.60	.56	.52	.49
			5	.57	.51	.47	.56	.51	.47	.55	.50	.46	.44
			6	.51	.45	.41	.51	.45	.41	.49	.44	.40	.38
			7	.46	.40	.35	.45	.39	.35	.44	.39	.35	.33
			8	.41	.35	.31	.41	.35	.31	.40	.34	.31	.29
			9	.37	.31	.27	.37	.31	.27	.36	.30	.27	.25

TABLE 16.1 Coefficients of Utilization for Typical Luminaires with Suggested Maximum Spacing Ratios (*Continued*)

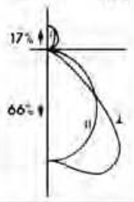
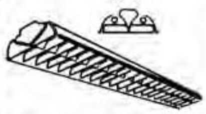
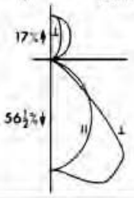
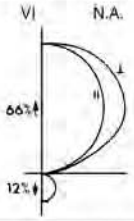
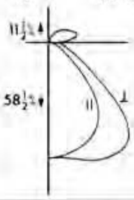
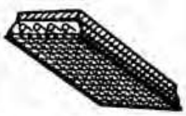
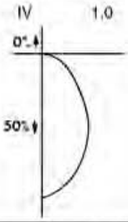
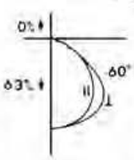
Typical Luminaire	Typical Distribution and Percent Lamp Lumens		ρ_{CC} →	80			70			50			0
			ρ_W →	50	30	10	50	30	10	50	30	10	0
	Maintenance Category	Maximum S/MH	RCR	Coefficients of Utilization for 20% Effective Floor Cavity Reflectance (ρ_{FC} = 20)									
26 	II	1.5/1.3	0	.95	.95	.95	.91	.91	.91	.83	.83	.83	.66
			1	.85	.82	.80	.82	.79	.77	.75	.73	.72	.59
			2	.76	.72	.68	.74	.70	.66	.68	.65	.62	.52
			3	.69	.63	.59	.66	.61	.57	.62	.58	.54	.46
			4	.62	.56	.51	.60	.54	.50	.56	.51	.47	.41
			5	.55	.49	.44	.53	.48	.43	.50	.45	.41	.36
			6	.50	.43	.39	.48	.42	.38	.45	.40	.36	.31
Diffuse aluminum reflector with 35° crosswise shielding			7	.45	.38	.34	.43	.37	.33	.41	.36	.32	.27
			8	.40	.34	.29	.39	.33	.29	.37	.31	.28	.24
			9	.36	.30	.25	.35	.29	.25	.33	.28	.24	.20
28 	II	1.5/1.1	0	.83	.83	.83	.79	.79	.79	.72	.72	.72	.56
			1	.75	.72	.70	.72	.69	.67	.65	.64	.62	.50
			2	.67	.63	.60	.65	.61	.58	.59	.57	.54	.45
			3	.61	.56	.52	.58	.54	.51	.54	.50	.48	.40
			4	.55	.49	.45	.53	.48	.44	.49	.45	.42	.36
			5	.49	.44	.40	.47	.42	.39	.44	.40	.37	.31
			6	.45	.39	.35	.43	.38	.34	.40	.36	.33	.28
Diffuse aluminum reflector with 35° crosswise, 35° lengthwise shielding			7	.40	.35	.31	.39	.34	.30	.36	.32	.29	.25
			8	.36	.31	.27	.35	.30	.26	.33	.28	.25	.21
			9	.33	.27	.23	.32	.26	.23	.29	.25	.22	.19
33 	VI	N.A.	0	.77	.77	.77	.68	.68	.68	.50	.50	.50	.12
			1	.67	.64	.62	.59	.57	.54	.44	.42	.41	.10
			2	.59	.54	.50	.52	.48	.45	.38	.36	.34	.09
			3	.51	.46	.42	.45	.41	.37	.34	.31	.28	.07
			4	.45	.40	.35	.40	.35	.31	.30	.27	.24	.06
			5	.40	.34	.30	.35	.30	.27	.26	.23	.20	.05
			6	.36	.30	.26	.32	.27	.23	.24	.20	.18	.05
Luminous bottom-suspended unit with very-high-output lamp			7	.32	.26	.22	.28	.23	.20	.21	.18	.15	.04
			8	.29	.23	.19	.25	.21	.17	.19	.16	.13	.03
			9	.26	.20	.17	.23	.18	.15	.17	.14	.12	.03
35 	V	1.5/1.2	0	.81	.81	.81	.78	.78	.78	.72	.72	.72	.59
			1	.71	.69	.66	.69	.66	.64	.64	.62	.60	.50
			2	.64	.59	.56	.61	.58	.54	.57	.54	.51	.44
			3	.57	.52	.48	.55	.50	.47	.51	.48	.45	.38
			4	.51	.46	.41	.49	.44	.41	.46	.42	.39	.34
			5	.46	.40	.36	.44	.39	.35	.41	.37	.34	.29
			6	.41	.35	.31	.40	.35	.31	.38	.33	.30	.26
Two-lamp prismatic wraparound; multiply by 0.95 for four lamps			7	.37	.31	.27	.36	.31	.27	.34	.29	.26	.23
			8	.33	.28	.24	.32	.27	.23	.30	.26	.22	.19
			9	.30	.24	.20	.29	.24	.20	.27	.23	.19	.17
38 	IV	1.0	0	.60	.60	.60	.58	.58	.58	.56	.56	.56	.50
			1	.54	.52	.50	.52	.51	.49	.50	.49	.48	.44
			2	.48	.45	.43	.47	.44	.42	.45	.43	.41	.39
			3	.43	.40	.37	.42	.39	.37	.41	.38	.36	.34
			4	.39	.35	.32	.38	.35	.32	.37	.34	.32	.30
			5	.35	.31	.28	.35	.31	.28	.34	.30	.28	.26
			6	.32	.28	.25	.32	.28	.25	.31	.27	.25	.23
Four-lamp, 610-mm (2-ft)-wide troffer with 45° plastic louver			7	.29	.25	.22	.29	.25	.22	.28	.25	.22	.21
			8	.26	.22	.20	.26	.22	.20	.25	.22	.20	.18
			9	.24	.20	.17	.24	.20	.17	.23	.20	.17	.16
42 	V	1.4/1.2	0	.75	.75	.75	.73	.73	.73	.70	.70	.70	.63
			1	.67	.65	.63	.66	.64	.62	.63	.62	.60	.55
			2	.60	.57	.54	.59	.56	.53	.57	.54	.52	.49
			3	.54	.50	.47	.53	.49	.46	.52	.48	.45	.43
			4	.49	.44	.40	.48	.44	.40	.47	.43	.40	.37
			5	.44	.39	.35	.43	.38	.35	.42	.38	.34	.33
			6	.40	.34	.31	.39	.34	.31	.38	.34	.30	.29
Fluorescent unit with flat prismatic lens, four-lamp, 610 mm (2 ft) wide			7	.36	.30	.27	.35	.30	.27	.34	.30	.27	.25
			8	.32	.27	.23	.32	.27	.23	.31	.26	.23	.22
			9	.29	.24	.20	.28	.23	.20	.28	.23	.20	.19

TABLE 16.1 Coefficients of Utilization for Typical Luminaires with Suggested Maximum Spacing Ratios (*Continued*)

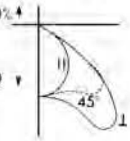
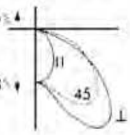
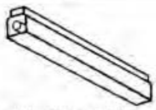
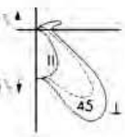
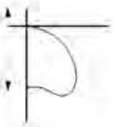
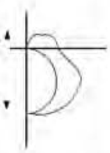
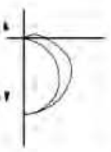
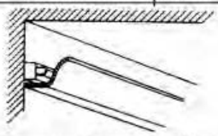
	Typical Distribution and Percent Lamp Lumens		ρ_{CC} →	80			70			50			0
			ρ_W →	50	30	10	50	30	10	50	30	10	0
Typical Luminaire	*Maintenance Category*	*Maximum S/MH*	*RCR*	*Coefficients of Utilization for 20% Effective Floor Cavity Reflectance (ρ_{FC} = 20)*									
44 	IV	N.A.	0	.71	.71	.71	.70	.70	.70	.66	.66	.66	.60
	0%↑  60↓		1	.65	.63	.61	.63	.62	.60	.61	.59	.58	.54
			2	.59	.55	.53	.58	.55	.52	.55	.53	.51	.48
			3	.53	.49	.46	.52	.48	.45	.50	.47	.45	.42
			4	.47	.43	.40	.47	.43	.40	.45	.42	.39	.37
			5	.42	.38	.34	.42	.37	.34	.41	.37	.34	.32
			6	.38	.33	.30	.38	.33	.30	.37	.33	.30	.28
			7	.34	.29	.26	.33	.29	.26	.33	.28	.25	.24
Radial batwing distribution—			8	.30	.25	.22	.30	.25	.22	.29	.25	.22	.20
louvered fluorescent unit			9	.27	.22	.18	.26	.22	.18	.26	.21	.18	.17
45 	V	N.A.	0	.57	.57	.57	.56	.56	.56	.53	.53	.53	.48
	0%↑  48%↓		1	.50	.48	.47	.49	.47	.46	.47	.46	.44	.41
			2	.44	.41	.38	.43	.40	.38	.41	.39	.37	.34
			3	.39	.35	.32	.38	.34	.31	.37	.33	.31	.29
			4	.34	.30	.27	.33	.29	.26	.32	.29	.26	.24
Radial batwing distribution—			5	.30	.25	.22	.29	.25	.22	.28	.24	.22	.20
four-lamp, 610-mm			6	.26	.22	.19	.26	.22	.18	.25	.21	.18	.17
(2 ft)-wide fluorescent unit			7	.23	.19	.16	.23	.19	.16	.22	.18	.16	.14
with flat prismatic lens			8	.21	.16	.13	20	.16	.13	.19	.16	.13	.12
and overlay			9	.18	.14	.11	.18	.14	.11	.17	.14	.11	.10
46 	V	N.A.	0	.87	.87	.87	.84	.84	.84	.77	.77	.77	.64
	12%↑  63½%↓		1	.76	.73	.70	.73	.70	.67	.67	.65	.63	.53
			2	.66	.61	.57	.64	.59	.56	.59	.56	.52	.44
			3	.59	.53	.48	.56	.51	.47	.53	.48	.44	.38
			4	.52	.45	.40	.50	.44	.40	.47	.42	.38	.32
Bilateral batwing distribu-			5	.46	.39	.34	.44	.38	.33	.41	.36	.32	.27
tion—one lamp, surface-			6	.41	.34	.29	.39	.33	.29	.37	.31	.27	.23
mounted fluorescent with			7	.36	.30	.25	.35	.29	.24	.33	.27	.23	.20
prismatic wraparound			8	.32	.26	.21	.31	.25	.21	.29	.24	.20	.17
lens			9	.29	.22	.18	.28	.22	.18	.26	.21	.17	.14
47 	V	1.7	0	.71	.71	.71	.69	.69	.69	.66	.66	.66	.60
	0%↑  59½%↓		1	.62	.60	.58	.61	.59	.57	.59	.57	.55	.51
			2	.55	.51	.47	.53	.50	.47	.51	.48	.46	.42
			3	.48	.43	.39	.47	.43	.39	.45	.41	.38	.36
			4	.42	.37	.33	.41	.37	.33	.40	.36	.32	.30
Radial batwing distribution—			5	.37	.32	.27	.36	.31	.27	.35	.30	.27	.25
four-lamp, 610-mm (2-ft)-			6	.33	.27	.23	.32	.27	.23	.31	.26	.23	.21
wide fluorescent unit with			7	.29	.24	.20	.29	.24	.20	.28	.23	.20	.18
flat prismatic lens—			8	.26	.21	.17	.25	.20	.17	.25	.20	.17	.15
see note 2			9	.23	.18	.14	23	.18	.14	.22	.17	.14	.13
48 	I	1.6/1.2	0	1.01	1.01	1.01	.96	.96	.96	.87	.87	.87	.68
	20½%↑  68%↓		1	.85	.81	.77	.81	.77	.73	.73	.70	.67	.53
			2	.73	.66	.61	.69	.63	.58	.63	.58	.54	.42
			3	.63	.56	.50	.60	.53	.48	.55	.49	.44	.35
			4	.56	.47	.41	.53	.46	.40	.48	.42	.37	.29
			5	.49	.40	.34	.46	.39	.33	.42	.36	.31	.24
			6	.43	.35	.29	.41	.34	.28	.38	.31	.26	.20
			7	.39	.31	.25	.37	.29	.24	.34	.27	.23	.17
Two-lamp fluorescent strip			8	.34	.27	.21	.33	.26	.21	.30	.24	.19	.15
unit			9	.31	.23	.18	.30	.23	.18	.27	.21	.17	.12
49 	I	1.4/1.2	0	1.13	1.13	1.13	1.09	1.09	1.09	1.01	1.01	1.01	.85
	12½%↑  85%↓		1	.96	.92	.88	.93	.89	.85	.87	.83	.80	.68
			2	.83	.76	.70	.80	.74	.68	.75	.69	.65	.55
			3	.73	.65	.58	.70	.63	.57	.66	.59	.54	.46
			4	.64	.55	.49	.62	.54	.48	.58	.51	.46	.39
			5	.56	.47	.41	.55	.46	.40	.51	.44	.38	.33
			6	.50	.41	.35	.49	.40	.34	.46	.38	.33	.28
Two-lamp fluorescent strip			7	.45	.36	.30	.44	.35	.30	.41	.34	.28	.24
unit with 235° reflector			8	.40	.32	.26	.39	.31	.25	.37	.30	.25	.21
fluorescent lamps			9	.36	.28	.22	.35	.27	.22	.33	.26	.21	.18

TABLE 16.1 Coefficients of Utilization for Typical Luminaires with Suggested Maximum Spacing Ratios (*Continued*)

Typical Luminaire	Typical Distribution and Percent Lamp Lumens; Maintenance Category, Maximum S/MH	RCR	ρ_{CC} → 80			70			50			0		
		ρ_W →	50	30	10	50	30	10	50	30	10	0		
			Coefficients of Utilization for 20% Effective Floor Cavity Reflectance (ρ_{FC} = 20)											
50 		1	.42	.40	.39	.36	.35	.33	.25	.24	.23	Coves are not recommended for lighting areas having low reflectances		
		2	.37	.34	.32	.32	.29	.27	.22	.20	.19			
		3	.32	.29	.26	.28	.25	.23	.19	.17	.16			
		4	.29	.25	.22	.25	.22	.19	.17	.15	.13			
		5	.25	.21	.18	.22	.19	.16	.15	.13	.11			
		6	.23	.19	.16	.20	.16	.14	.14	.12	.10			
Single-row fluorescent lamp cove without reflector (multiply by 0.93 for two rows and by 0.85 for three rows)		7	.20	.17	.14	.17	.14	.12	.12	.10	.09			
		8	.18	.15	.12	.16	.13	.10	.11	.09	.08			
		9	.17	.13	.10	.15	.11	.09	.10	.08	.07			
												ρ_{CC} = 10%, ρ_W =		
												50	30	10
53 ρ_{CC} from below ~45% 		1							.51	.49	.48	.47	.46	.45
		2							.46	.44	.42	.43	.42	.40
		3							.42	.39	.37	.39	.38	.36
		4							.38	.35	.33	.36	.34	.32
		5							.35	.32	.29	.33	.31	.29
		6							.32	.29	.26	.30	.28	.26
Louvered ceiling. Ceiling efficiency ~50; 45° shielding opaque louvers of 80% reflectance. Cavity with minimum obstructions and painted with 80% reflectance paint—use ρ_{CC} = 50.		7							.29	.26	.23	.28	.25	.23
		8							.27	.23	.21	.26	.23	.21
		9							.24	.21	.19	.24	.21	.19
		10							.22	.19	.17	.22	.19	.17

Source: Data extracted from *IES Lighting Handbook Reference Volume*, (1981): with permission.

Notes:
1. Refer to the manufacturer's catalog data for more precise values when a specific luminaire type is proposed for use.
2. Multiply coefficients by 1.05 for three lamps and by 1.1 for two lamps.

under each one. This ignores (deliberately) any contributions from other fixtures in a multifixture installation and from interreflections, accounting only for the direct component of illuminance from the two test fixtures. Therefore, in an actual installation with several rows of fixtures, the illuminance at point P_1 in Fig. 16.16 is *higher* than the average by 20% to 30% because of the other fixtures and interreflections, and the illuminance at point P_2 is approximately equal to the room average. The illuminance levels along the walls, assuming a distance between the last row and the wall equal to one-half of the side-to-side spacing, range from 60% of average at point P_3 down to 50% at point P_4, assuming light-colored walls.

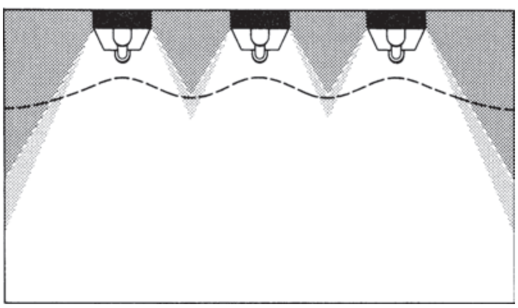


Fig. 16.15 *The ratio of maximum to minimum illuminance should not exceed 1.3 in areas requiring uniform illumination.*

When walls are dark due to paint or aging, bookshelves, dark wood paneling, and the like, the illuminance levels drop to less than 50% of average, which is insufficient as task lighting. To counteract this effect, particularly when placement of furniture is such that visual tasks *will* occur near walls, the designer has three choices:

1. Reduce the distance between the last row of fixtures and the wall to a third or less of the row-to-row spacing. This also provides required wall lighting.

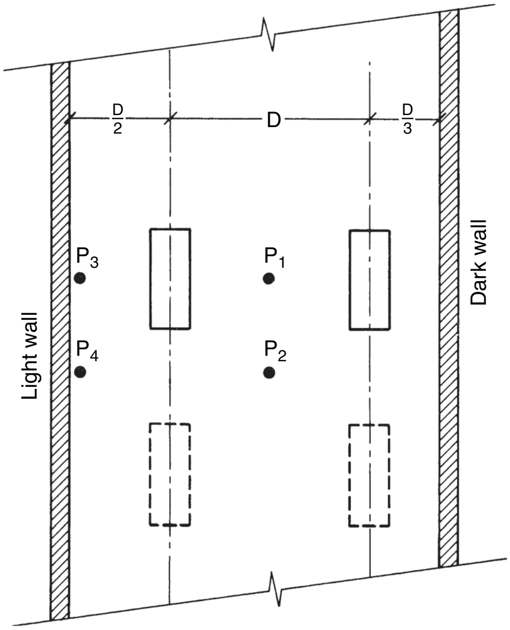


Fig. 16.16 *The diagram shows lighting fixtures installed according to the manufacturer's recommended spacing criteria (ratio of spacing to mounting height above the work plane), with a row-to-row spacing, D, and a row-to-wall spacing, D/2, as shown at the left wall. Assuming a high-reflectance finish on the wall (light color), illuminances P_3 and P_4 are at least one-half of the illuminance directly below a fixture. At a dark wall, as on the right, illuminance would fall below this value. As a consequence, the designer would move the right row of luminaires closer to the wall, as shown.*

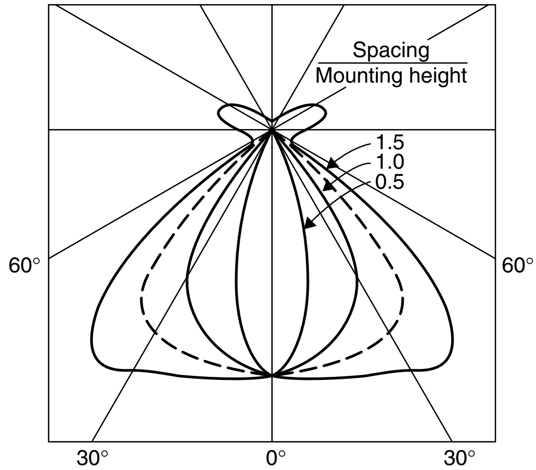


Fig. 16.17 *Typical distribution curves for approximating the ratio of fixture spacing to mounting height (S/MH) above the working plane for direct distribution luminaires. Although these curves were developed for point sources such as incandescent (and HID), they can also be applied to asymmetric distribution luminaires using fluorescent lamps. The permissible S/MH is somewhat higher than the curves indicate because this is a semi-direct distribution, and the ceiling light component permits wider spacing between units. (After Odle and Smith, from* IESNA Journal, *January 1963.)*

2. Provide some type of continuous perimeter lighting or wallwash units, both of which increase illuminance levels at the walls.
3. A combination of choices 1 and 2.

Because endwise illumination from linear fluorescent fixtures is considerably lower than crosswise illumination, end walls have lower illuminance than side walls and greater illuminance variation. It is, therefore, particularly important to provide some additional illumination, as discussed previously, and terminate fixture rows no more than 1 ft from an end wall. This is all the more important where visual tasks without supplementary task lighting occur at these walls.

We mentioned previously that the fixture in Fig. 16.1*a* had a high S/MH because of its flat-bottomed curve. This ratio, when not given by the manufacturer, may be approximated from Fig. 16.17. An accurate method of calculating maximum to minimum illumination ratios is available (see the *IESNA Lighting Handbook*).

The foregoing discussion of illumination uniformity was concerned with uniformity on a horizontal work plane. Occasionally, it is necessary to know the degree of uniformity vertically—that is, on horizontal planes at different elevations *directly below the fixtures*. Four different lighting situations are normally encountered. They are point sources, such as point source downlights; line sources, such as continuous-row fluorescent fixtures; infinite sources, such as luminous ceilings—whether transilluminated or indirect; and parabolic reflector beams, such as from parabolic aluminized reflector (PAR) lamps. The vertical uniformity of each type is shown graphically in Fig. 16.18.

16.6 LUMINAIRE MOUNTING HEIGHT

The mounting height of luminaires is normally established before their spacing. In arriving at a mounting height for fixtures with an upward

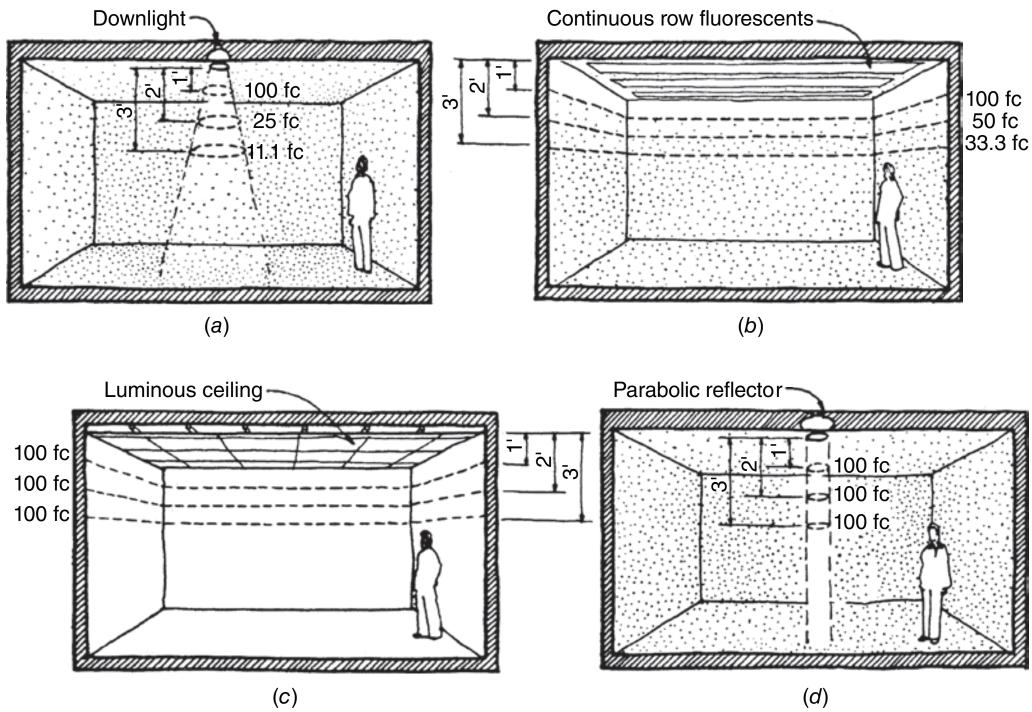


Fig. 16.18 *Variation of illuminance vertically, directly below the fixtures, for different source types. (a, b) Illuminance directly below the fixture varies inversely with the square of the distance for a point source and inversely with the distance for a line source. (c, d) Illuminance remains constant at all distances from either an infinite (or nearly) source or a parabolic reflector.*

component, a balance must be struck between low mounting, which controls ceiling brightness and gives good utilization of light, and a reluctance to dominate an area, particularly a large room, by using such a low mounting height that the apparent ceiling height is affected (Fig. 16.19). General rules for mounting height are:

1. Indirect and semi-indirect luminaires should normally be suspended no less than 18 in. (460 mm) from the ceiling and preferably 24 to 36 in. (610 to 915 mm). Single-lamp luminaires with a very wide distribution (inverted batwing) may be suspended as little as 12 in. (305 mm) from the ceiling. Manufacturers' recommendations should be sought on this point.
2. Direct–indirect and semi-direct fluorescent fixtures should be suspended not less than 12 in. (305 mm) for two-lamp units and 18 in. (460 mm) for three- and four-lamp units.

The effect of pendant length on the coefficient of utilization (efficiency; see Section 16.11) is given in Fig. 16.20.

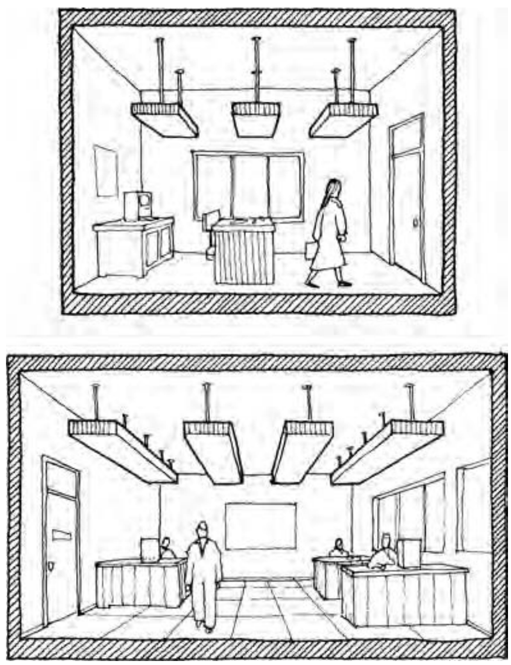


Fig. 16.19 *Mounting height of fixtures may be lower in a small room than in a large room because of the illusion of lowness created in a large room.*

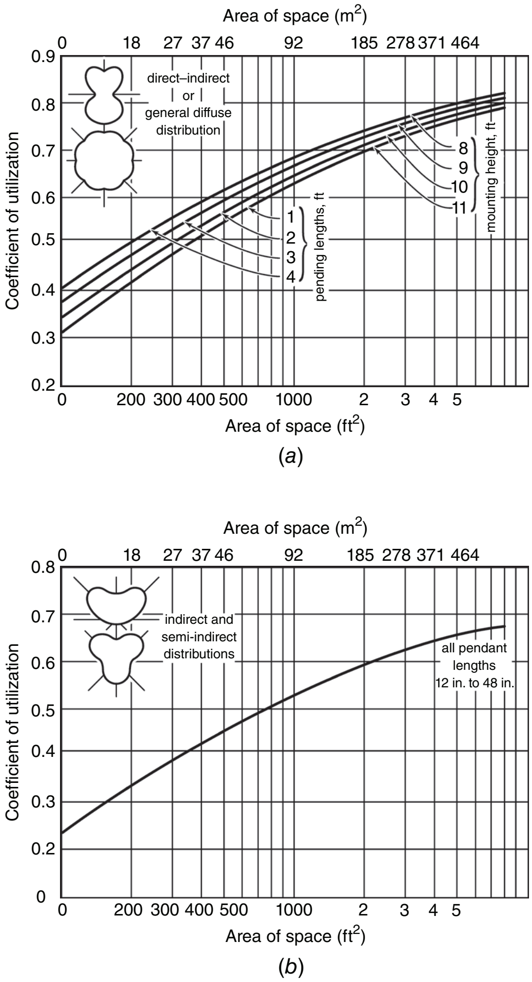


Fig. 16.20 Coefficient of utilization (CU; lighting system efficiency) as a function of pendant length for various distributions. With a substantial downward component, as in direct–indirect or general diffuse lighting (a), system efficiency rises slowly as the fixture descends (pendant length increases). Maximum differentials occur in small rooms and can reach 20%. Where the ceiling is the light source, as in indirect and semi-indirect systems (b), the pendant length does not change the room illumination. This curve can be used to estimate CU for indirect and semi-indirect luminaries in the absence of manufacturer's data. (Redrawn with SI units by Lisa Leal.)

16.7 LIGHTING FIXTURES

Before proceeding further with design, we will discuss the principal item of lighting hardware: the luminaire itself. This section and the sections that follow cover luminaire construction, installation, and appraisal. The architect should consider that electric lighting fixtures constitute 25% to 30% of the electrical budget or 4% to 5% of the overall building budget. Because the difference between a high-quality unit and an inferior one is often not readily visible to the casual observer, particular care must be taken in the specification of lighting fixtures and in the examination of submittals (shop drawings) and samples. All fixtures, if applied properly, give a sufficient quantity of light, but only a good unit combines quantity with good quality, ease of installation, ease of maintenance, and indefinite life. In addition, installation must be proper to ensure mechanical rigidity and safety, electrical safety, freedom from excessive temperatures, and requisite accessibility of component parts and of the fixture outlet box. The following material is a combination of *National Electrical Code* (*NEC*) minimum requirements and factors beyond these minima that the authors have found important.

16.8 LIGHTING FIXTURE CONSTRUCTION

1. All fixtures should be wired and constructed to comply with local codes, *NEC* (Article 410), and the Underwriters Laboratories (UL) Standard for Luminaires, and should bear the UL label where label service is available. Reflective Luminaire Manufacturer (RLM) standards should be adhered to for all porcelain-enameled fixtures.
2. Fixtures should generally be constructed of 20-gauge (0.0359-in. [0.9-mm]) steel (at minimum). Cast portions of fixtures should be no less than $\frac{1}{16}$ in. thick.
3. All metals should be coated. The final coat should be a baked-enamel white paint of at least 85% reflectance, except for anodized, aluminum, or silvered surfaces.
4. No point on the outside surface of any fixture should exceed 90°C after installation and on continuous operation. For an exception, see *NEC* Article 410 M.
5. Each fixture should be identified by a label carrying the manufacturer's name and address and the fixture catalog number.
6. Glass diffuser panels in fluorescent fixtures should be mounted in a metal frame. Plastic

diffusers should be suitably hinged. "Lay-in" plastic diffusers should not be used.

7. Plastic diffusers should be of the slow-burning or self-extinguishing type with a low smoke-density rating and low heat-distortion temperatures. The latter should be low enough so that the plastic diffuser distorts sufficiently to drop out of the fixture before reaching ignition temperature.
8. It is *imperative* that plastics used in air-handling fixtures be of the noncombustible, low-smoke-density type. These requirements also apply to other nonmetallic components of such fixtures.
9. All plastic diffusers should be clearly marked with their composition material, trade name, and manufacturer's name and identification number. Results of ASTM combustion tests should be submitted with fixture shop drawings. The characteristics of many plastic diffusers change radically with age and exposure to UV radiation.

   A brief survey of the most common standard transparent and translucent lighting fixture diffusers follows.

   Glass. Transparent to translucent, scratch resistant, easily cleaned, nonflammable, available in all grades of impact resistance, non-yellowing, usable with all sources, unaffected by and effective in blocking UV, readily formed into desired patterns. Heavy and expensive.

   Acrylic (Plexiglas). Clear to translucent, easily scratched, slow burning, low impact resistance, resistant to yellowing, and available in a special low-yellowing composition (UV grade). Usable indoors and outdoors. Not usable at the elevated temperatures (>90°C [194°F]) found in some HID applications. Does not readily embrittle, warp, or craze. Molds well.

   Polycarbonate. Initially very clear and highly impact resistant, but with a tendency to opacity and strength loss with age. Good scratch resistance and excellent thermal resistance. Usable indoors and outdoors with all sources. Readily molded to prismatic forms. Self-extinguishing (burning rate). Expensive.

   Polystyrene. Usable only indoors because of rapid yellowing when exposed to exterior UV radiation. Slow burning, but smoke-generation properties problematic with some fire codes. Not usable in the long term because of discoloration, particularly with UV-producing sources. Good thermal resistance. Readily molded. Cheap. Not scratch resistant.

   As can readily be seen, no ideal diffuser material exists. A designer must select the material that best suits the use and budget, considering both initial and replacement costs as well as long-term optical properties.
10. Ballasts should be mounted in fixtures with captive screws on the fixture body to allow ballast replacement without fixture removal.
11. All fixtures mounted outdoors, whether under canopies or directly exposed to the weather, should be constructed of appropriate weather-resistant materials and finishes, including gasketing to prevent entrance of water into wiring, and should be marked by the manufacturer as being "Suitable for Outdoor Use."

16.9 LIGHTING FIXTURE STRUCTURAL SUPPORT

Although some codes allow fluorescent fixtures weighing less than 40 lb (18 kg) to be mounted directly on the horizontal metal members of hung-ceiling systems, experience has shown that vibration, member deflection, routine maintenance operation on equipment in hung ceilings, and poor workmanship can cause such fixtures to fall, endangering life. It is therefore strongly recommended that all fixtures—surface, pendant, or recessed—whether mounted individually or in rows, be supported from the ceiling system support (purlins) or directly from the building structure, but in no case by the ceiling system itself. This is particularly important in the case of an exposed "Z" spline ceiling system.

16.10 LIGHTING FIXTURE APPRAISAL

The intense competition in the lighting products field necessitates close scrutiny of the characteristics of luminaires and all accessories. To compare the relative merits of similar lighting fixtures manufactured by different companies, complete test data plus a sample in a regular shipping carton from a normal manufacturing run are needed.

The following list should be used as a basic guide, with additional items added according to job requirements:

1. *Photometric and design data.* Manufacturers should furnish complete test data, including candlepower distribution curve(s), coefficients of utilization, wall and ceiling luminance coefficients, luminance data from 45° to 85°, a table of VCP, energy data including LER (see Section 16.12), and recommended S/MH (SC). These data should come from a reliable independent testing laboratory, not from the manufacturer's test facilities. In addition, many manufacturers either regularly publish or make available on request various design aids such as isolux (isocandle) curves and point-by-point computer printouts for different layouts.
2. *Construction and installation.* The designer should check the sample for workmanship; rigidity; quality of materials and finish; and ease of installation, wiring, and leveling. Installation instruction sheets should be sufficiently detailed. Results of actual operating temperature tests in various installation modes should be included. Air-handling fixtures should be furnished with heat-removal data, pressure-drop curves, air-diffusion data, and noise criteria (NC) data for different airflow rates.
3. *Maintenance.* Luminaires should be simply and quickly relampable, resistant to dirt collection, and simple to clean. Replacement parts must be readily available.

16.11 LUMINAIRE–ROOM SYSTEM EFFICIENCY: COEFFICIENT OF UTILIZATION

Because of internal reflections inside a luminaire, some of the generated lumen output of the lamp is lost. The ratio of output lumens to lamp (input) lumens, expressed as a percentage, represents the luminous efficiency of the fixture. This characteristic has little meaning by itself, however, because the efficiency of a luminaire in doing a particular lighting job depends on the space in which it is used.

To illustrate, consider the case of a large room with a high, dark ceiling. If we were to use a high-efficiency (say, 80%) indirect lighting unit in such a room, most of the light directed upward would be lost (absorbed), and the actual illuminance on the working plane would be very low. If, however, the same room were illuminated with 50% efficiency direct-lighting units utilizing the same wattage, the illuminance on the working plane would be considerably higher than in the first case.

Similarly, if we consider a small room with dark walls and ceiling, lighted alternatively by diffuse lighting and direct lighting units of the same wattage and unit efficiency, the horizontal-plane illumination is higher for the direct units because of the large loss of the horizontal and upward components of the diffuse lighting on the walls and ceiling. Fixture efficiency *alone* is not sufficient; *the overall luminous efficiency of a particular unit in a particular space* is the required figure of merit. This number, inasmuch as it describes the utilization of the fixture output in a specific space, is known as the *coefficient of utilization* (CU). It is defined as the ratio between the lumens reaching the horizontal work plane and the generated lumens. As each luminaire has a different coefficient for every different space in which it is used, a system of standardization has evolved utilizing room cavities (explained later) of certain proportions and various surface reflectances. The fixture coefficients are then computed and tabulated as shown in Table 16.1. It should be emphasized that the figures given in this table are for generic fixture types only; in an actual job, luminaire data as found in manufacturers' catalogs should be used. To summarize, CU is a factor that combines fixture efficiency and distribution with room proportions, mounting height, and surface reflectances.

16.12 LUMINAIRE EFFICACY RATING

As a result of a U.S. Energy Policy Act (EPACT) mandate calling for an industry-wide testing and information program designed to improve lighting fixture energy efficiency, a collaborative effort produced NEMA Standard LE5, *Procedure for Determining Efficacy of Luminaires*. Unlike the CU discussed in the previous section, which defines the illumination efficiency of a particular luminaire in a particular space, Standard LE5 determines the energy efficiency of the luminaire *alone*. Because this efficiency is expressed in lumens per watt (lumens output per watt input), it uses the same descriptive term used for light sources (i.e., *efficacy*). This metric takes into account all power used by a luminaire, including ballast, and includes the ballast factor, which is itself a ballast energy efficiency metric. The expression used to calculate the luminaire efficacy rating (LER) is

$$\text{LER} = \frac{\text{photometric efficiency} \times \text{ballast factor}}{\text{luminaire input watts}}$$

An LER metric applies to a specific type of fluorescent luminaire and is identified by an abbreviation as

FL = fluorescent lensed
FP = fluorescent parabolic
FW = fluorescent wraparound
FI = fluorescent industrial
FS = fluorescent strip light

Thus, the energy figures shown in Fig. 16.14 are specifically labeled “FP” to denote a fluorescent parabolic luminaire. This enables a designer to compare LER figures for different fixtures on a common basis. This commonality also extends to ballast type (i.e., magnetic or electronic). In addition, Standard LE5 lists benchmark LER figures that are considered to represent an acceptable luminaire. An additional item of data useful in economic comparisons that is included in the NEMA standard is the yearly cost per 1000/lm, based on 3000 burning hours and $0.08 per kilowatt-hour (see Fig. 16.14). The actual cost is easily calculated from this figure.

The LER approach has been expanded beyond fluorescent fixtures to include “Commercial, Nonresidential Downlight Luminaires” (NEMA LE5A [NEMA, 1999]) and “High-Intensity Discharge Industrial Luminaires” (NEMA LE5B [NEMA, 1998]).

LIGHTING CONTROL

16.13 REQUIREMENT FOR LIGHTING CONTROL

The term *lighting control* means all the techniques by which a lighting system can be operated, and covers both manual and automatic controls. The control strategy must be decided on simultaneously with the lighting design because the control scheme must be appropriate to the light source. In turn, the system’s accessories and arrangement depend on the control scheme. For instance, if dimming is decided on, using a fluorescent light source, then the range of dimming determines the type of ballast, the ballast switching points, and the degree of dimming flexibility.

The primary purposes of lighting control are flexibility and economy: flexibility to provide the modifications of luminances and patterns desired by the designer, and economy of both energy resources and monetary resources (see Appendix J for treatment of economic analyses). A properly designed lighting control system can reduce energy usage up to 60% over a simple on–off system installation. In addition, financial operating economies result from

- Reduced energy use
- Reduced air-conditioning costs as a result of lower lighting waste heat
- Longer lamp and ballast life due to lower operating temperatures and lower output
- Lower labor costs due to control automation

As noted previously (Chapter 13), lighting in most new nonresidential construction is designed within the energy constraints of ANSI/ASHRAE/IESNA Standard 90.1. This standard has a system of lighting power credits for lighting control systems designed with automatic energy-conserving controls. These credits permit the effective connected load to be reduced by factors that increase with energy conservation effectiveness. Thus, for example, circuits with a simple on-off mode initiated by a daylight sensor have a smaller power credit than daylight sensing with continuous dimming, because the latter is more energy economical (but much more expensive initially). To avoid confusion, particularly in view of overlapping and sometimes inaccurate terminology, it is necessary to differentiate between control functions, control devices, and control systems.

For lighting, the only control *functions* are switching and dimming. The control *devices* are the means by which the switching and dimming functions are accomplished. They are numerous, ranging from a simple wall switch to time switches and dimmers of all sorts. Generally also included in this category are control *initiation* devices, such as occupancy sensors and photocells. The control *system* is the entire assembly of control and signal-initiating equipment together with their interconnections. Included here also are microprocessors and programmable controllers. The system can be a stand-alone arrangement or, alternatively, as is the case in large facilities, it can be part of an energy management system (EMS), a building automation system (BAS), or both. The difference in operation in these instances lies in the control algorithm, which is primarily energy oriented for an EMS, and overall-building-function oriented for a BAS. In the discussion that follows, the control criteria are energy conservation, cost reduction, and operating flexibility.

16.14 LIGHTING CONTROL: SWITCHING

There are two basic control functions—switching and dimming. Switching is an on-off function. By selecting the number of lighting elements to be switched in each switching action, the designer can establish the number of control levels. The more levels, the finer the control. Thus, in a space requiring several levels of uniform illumination for different functions, the designer has many control alternatives. He or she can switch entire fixtures, but this adversely affects uniformity. Taking three-lamp fluorescent fixtures as an example, the designer can obtain better uniformity and four levels of illumination by switching the ballasts (assuming one two-lamp and half of a two-lamp ballast per fixture):

All ballasts on	100% illumination
Two-lamp ballast on	66% illumination
Half of two-lamp ballast on	33% illumination
All ballasts off	0% illumination

(Magnetic ballasts have historically been preferred for this arrangement because a single electronic ballast is often used for up to four lamps as one means of obtaining its benefits while reducing its cost per lamp.)

This type of switching has the advantage of light reduction in relatively small steps at low cost. A typical arrangement is shown in Fig. 16.21. Use of split-wired two-lamp units is advantageous from the cost and energy viewpoints. Even more uniform light reduction and finer control are possible with two-level ballasts (at increased cost). There, each lamp remains lighted but at either full or half output. Thus, the designer could have 0%, 50%, and 100% levels or, by combining alternate ballast switching with two-level ballasts, could have 0%, 17%, 33%, 50%, 67%, 83%, and 100% levels. However, if that degree of control is desirable, dimming is probably preferable. The choice depends on the type of space and on the situation economics, as discussed later. An alternative method of achieving lower lighting levels in discrete steps, by switching, is to introduce impedance into the lighting circuit.

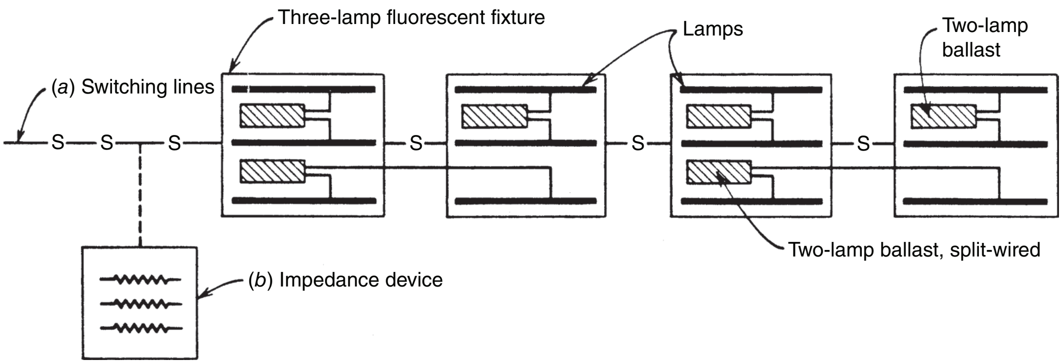


Fig. 16.21 *Schematic diagram of switching arrangements to achieve multiple discreet lighting levels with three-lamp fluorescent lighting fixtures. Two-lamp ballasts are used in the interest of energy conservation and financial economy. In scheme (a) ballasts are switched, thus removing either one or two lamps from service. Finer control is achieved by using two-level ballasts or by introducing impedance (b) into the circuit, either in a block for an entire circuit or distributed in each fixture.*

This acts to reduce circuit current and light output. Such devices are readily available for control of fluorescent lamps (see Fig. 16.25).

Recognition of the fact that an increased number of control (switch) points makes possible finer control, and therefore energy conservation, led to requirements in ANSI/ASHRAE/IESNA Standard 90.1 relating to the number of control points in a space and their types. Many field studies have demonstrated conclusively that reliance on manual switching is not an effective long-term energy conservation strategy, regardless of the good intentions of the space occupants. Indeed, studies have shown that space "ownership" affects even the low level of conservation possible with manual switching (i.e., lighting in private offices, conference rooms, and small storage spaces may be switched off, whereas lighting in multi-occupancy and common-use spaces such as libraries, large office spaces, break areas, and the like, may not). As a result, Standard 90.1 first specifies the minimum number of control points required in a space and then awards automatic switching or dimming a higher number of equivalent control points.

The basic requirement is for one control point for every 450 ft^2 (42 m^2) or fraction thereof of enclosed lighted space, plus one control point for each task (or group of tasks) located in the space. Thus, the classroom in Example 16.1 would require two control points for its 517 ft^2 (48 m^2) of area plus one control point for all similar tasks grouped in the room, for a total of three control points. This requirement could be met with three wall switches, or one wall switch and an occupancy sensor, or an automatic dimming system probably initiated by daylight sensors. The point is, of course, to encourage use of automatic controls, which, as has been pointed out repeatedly, is the only proven method of attaining significant energy conservation.

16.15 LIGHTING CONTROL: DIMMING

The techniques and equipment required for dimming each of the different light sources, as well as the effect on the color of the light produced and on the lamp, are discussed in Chapter 14. Figure 16.22 shows typical lumen output versus power input curves for common light sources. Note that for fluorescent lamps, *even with conventional magnetic*

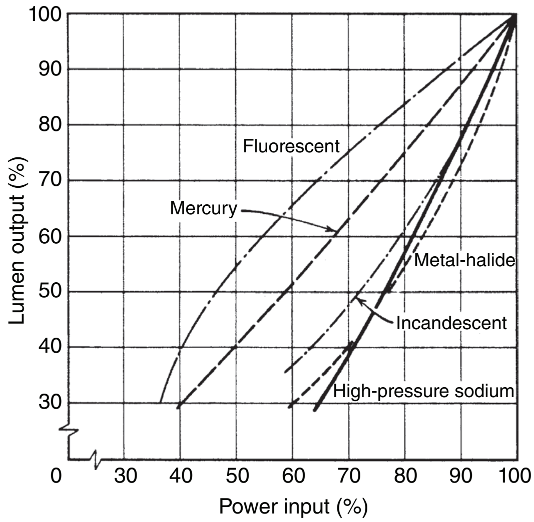


Fig. 16.22 *Typical dimming curves for generic light source types. Note that fluorescent lighting is efficient and approximately linear down to 40% output. All other sources have reduced efficacy when dimmed.*

ballasts, dimming down to approximately 40% of output is possible without reducing efficacy. This desirable characteristic can be exploited in control schemes where it is desired to change light output gradually without sacrificing efficiency. Due to efficacy reduction below 40% output, an economical and efficient control scheme combines dimming and switching of multi-lamp fluorescent fixtures to yield an almost stepless output range of 13% to 100% output. Continuous dimming over a 10% to 100% range is practical with special individual magnetic dimming ballasts or with electronic ballasts. As discussed in Chapter 14, electronic ballasts are much more energy-efficient than conventional ones and must be considered for all *new* installations, dimmed or not. For retrofit work, silicon-controlled rectifier (SCR) or triac dimmers give excellent results with existing conventional core-and-coil ballasts down to 40% output.

16.16 LIGHTING CONTROL: CONTROL INITIATION

Control initiation is either manual, automatic, or a combined manual-automatic function. The last is usually in the form of an override function: manual override of an automated procedure to ensure adequate control for special or unusual situations and automatic reset of the manual function to reestablish normal or steady-state operation.

(a) Manual Control Initiation

Numerous studies dating back at least 50 years have indicated increased employee satisfaction when at least a degree of control of the working environment is in his or her hands. This satisfaction is frequently accompanied by increased work output, at least in the short term. Unfortunately, manual control of lighting levels has been demonstrated to be wasteful of energy due to the tendency to leave lights on at maximum level even when daylight is supplying more than enough light or when leaving a room for an extended period. A modicum of energy conservation in the latter instance is possible with the installation of *time-out* switches in spaces normally used for short periods, such as supply closets (see Fig. 27.46). However, for normal working spaces, even installation of manual dimmers in private offices is not effective because of the need to go to the dimmer control location on the wall to readjust. Manual dimming in multiple-occupancy spaces is effective only in creating personnel dissatisfaction and friction.

There are practical remote-control dimming systems that can control single or multiple luminaires, making them applicable to all occupancies. Figure 16.23 illustrates the use of such a system in an open multiple-occupancy space. This enables individual workers to adjust the output of luminaire(s) closest to their workstation without disturbing other employees. This adjustment, which is simply accomplished (see Fig. 16.23*a*) by remote control, can alleviate direct and reflected glare or can be a temporary expedient suitable to the task at hand, as, for instance, work with a digital display. Figure 16.23*b*–*d* shows the system components. Wiring of the system can be arranged so that a single receiver/dimmer can control up to 20 ballasts or, conversely, multiple dimmers may be connected on a single circuit. The latter arrangement would be used in wiring a group of small single- or double-occupancy rooms. Such rooms are frequently wired with a wall-mounted dimmer, which can then be activated by the remote control, as shown in Fig. 16.24.

(b) Automatic Control Initiation

Automatic controls are of two types: an open-circuit type and a closed-loop feedback type, also known as *static* and *dynamic control*, respectively. The former initiates a control function that is independent of the actual lighting situation, whereas the latter reacts to the condition of the lighting situation it controls via a feedback loop.

1. *Static control.* The most common type of open-circuit lighting control is the programmable time-base controller. These vary from small, relatively simple units that replace wall switches and fit into a common device box to the more sophisticated units shown in Figs. 27.13. These devices are available in myriad designs and capacities, but all perform the same basic function—(remote) control of loads and circuits on a preprogrammed time basis. The programming, in turn, is determined after analysis of operating schedules, task requirements, and field conditions. With "tight" programming, energy savings of up to 50% over an uncontrolled installation are possible.

   Because these devices act only on a time base and are insensitive to actual field conditions, an override feature must be incorporated to permit accommodation of special conditions. Thus, if a timer is set to shut off a row of fixtures adjacent to windows between 10:00 A.M. and 3:00 P.M., local override must be provided to accommodate dark rainy days and the like. Similarly, if lighting is shut off during nonworking hours, provision must be made for persons working overtime. The override arrangement can be entirely local, in which case it may lead to energy waste because it depends on local cancellation; it can be local with time-out, which can be a nuisance to a person working for an extended period; or it can incorporate an override feedback link to the controller, usually operated by telephone lines. In general, programmable time controls are best applied to facilities with regular, repetitive schedules and few exceptional situations.
2. *Dynamic control.* The second type of automatic control initiation responds to sensor-indicated field conditions via an information feedback loop. It is frequently referred to as *dynamic control* because the initiation of a control

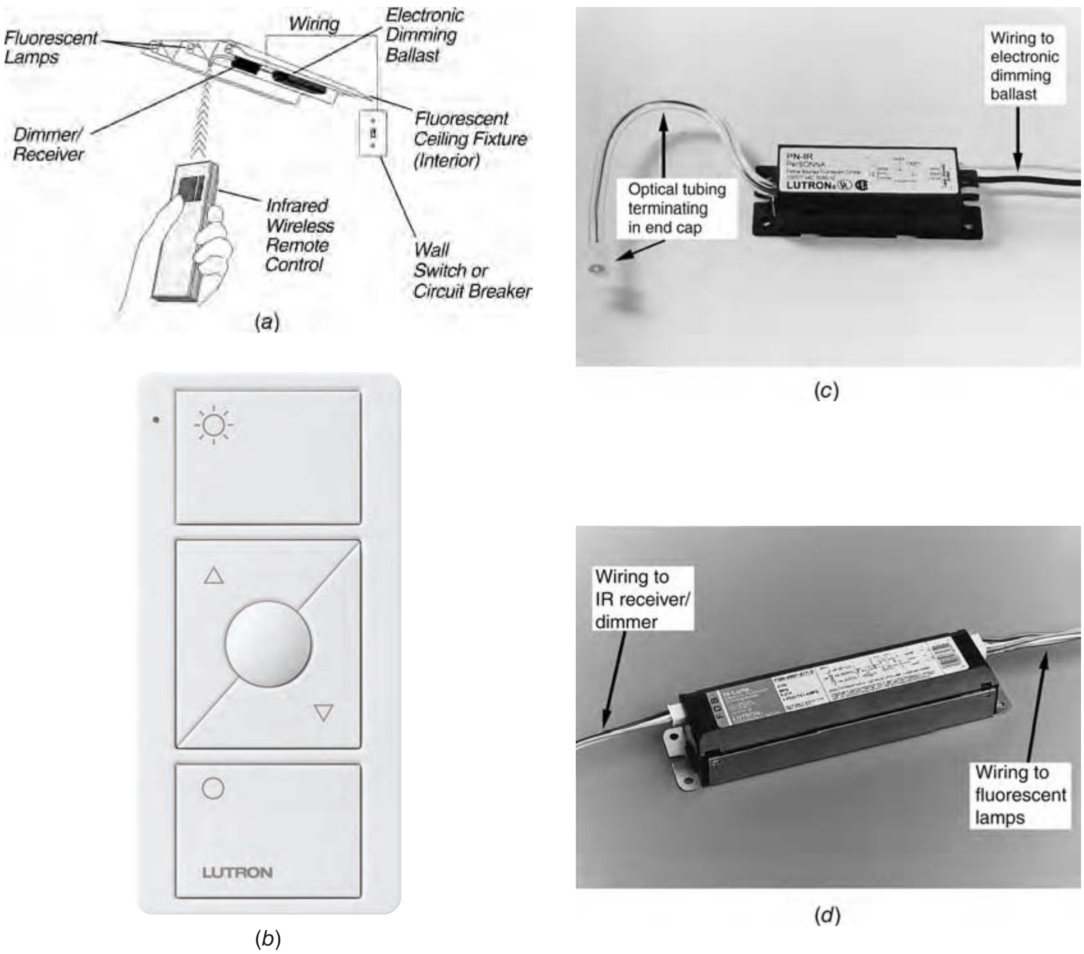


Fig. 16.23 *(a) Ceiling-mounted fluorescent fixtures within an 8-ft (2.4-m) radius of the optical sensor can be dimmed by remote control and restored almost instantaneously. (b) The handheld IR remote-control device for continuous dimming and for dimming override for maximum or minimum light. (c) The IR-activated receiver/dimmer, which fits into a 4-in (100-mm) square standard outlet box, can be mounted inside the luminaire as in (a) or adjacent to it. (d) High-frequency electronic dimming ballast for one to four lamps can provide full-range dimming down to 1–5% of output or down to 10% of output, depending on the type. The optical tube that carries the IR signal must be exposed on the ceiling. It may be mounted on the underside of an open luminaire or close by. (Courtesy of Lutron Electronics Co.)*

function depends not on a fixed programmed parameter such as time, but on real-time field parameters (i.e., as measured at that instant). In the case of lighting control, these parameters may be ambient illuminance, time, system kW demand, kWh usage in a time period, or space occupancy, singly or in combination, depending on the programming algorithm (i.e., how the controller's microprocessor has been programmed). The control device in its entirety is called a *programmable controller* (see Section 27.16), which, in combination with the field sensors and the interconnecting wiring, constitute the control system. Some systems are wireless, using high-frequency signals impressed on the power wiring system to transmit control signals. This arrangement is known as a *power line carrier* (PLC) system and is discussed in Section 27.34. Other systems are completely wireless, using radio frequencies and a system of wireless transmitters and receivers.

In addition to its CPU (microprocessor), a programmable controller contains input/output (I/O) interfaces, memory, and means for programming (and reprogramming). An operational block

Fig. 16.24 *Remote controller may be used to operate a wall-mounted dimmer. (Courtesy of Lutron Electronics Co.)*

diagram is shown in Fig. 27.14. The controller accepts not only the usual time-based signal function, but also information (feedback) from field devices via its I/O device. It then "processes" the signal in its CPU, which consists of logic and storage memory, and sends out a resultant processed control signal.

Large lighting control systems use a computer in lieu of a programmable controller and usually have additional control facilities, such as telephone interfaces and local control/relay/switching centers, which process local sensor input and control local lighting blocks (see Fig. 27.54). Identical systems are used for building automation (Chapter 31), HVAC control, energy management, and the like, the difference being the types of sensing devices and the control algorithm.

16.17 LIGHTING CONTROL STRATEGY

A good lighting control system varies the lighting supplied to match the lighting required, *as the requirement varies*; thus, overlighting and underlighting are avoided. In addition, the control system must be capable of permitting initial adjustments and of accommodating external, non-lighting-connected constraints such as commands from a peak-demand controller. The common lighting system situations addressed by a control system follow.

(a) System "Tuning"

In every lighting installation there is a difference between the design intent and the field result. This is due to assumptions and imprecision in calculation, differences between specified and installed equipment, equipment location changes, and so on. The responsible lighting designer "tunes" the lighting system in the field to attain the intended design. This usually means *reducing lighting levels* in nontask areas because spill light is frequently sufficient for circulation, rough material handling, and the like. This tuning can result in an energy reduction of 20% to 30%, depending on the control technique.

The smaller the group of light sources controlled, the more accurate the tuning and the larger the energy saving proportionally. Lighting system retuning is also required when the function of an entire space is changed, or when a single area is altered by a furniture move or by a task change. An ancillary benefit of field tuning is glare reduction, which frequently improves task visibility dramatically. Tuning is a one-step function in the sense that, once accomplished, it does not require change unless the space function changes. Therefore, it should also be reversible to accommodate such changes. Tuning should not be confused with *lumen maintenance*, described in Section 16.17*d*, which is a control strategy designed to compensate for normal system output decline and its corollary—initial system overdesign.

As stated, the tuning action most often required is a reduction in illuminance. This can be accomplished by:

1. Making appropriate field modifications to adjustable fixtures (aiming, lamp position, etc.)
2. Replacing lamps with others of lower wattages and replacing fluorescent tubes with low-wattage tubes—changes that reduce light output reversibly
3. Replacing fluorescent ballasts with low-current ballasts, thereby lowering output
4. Adding current-limiting impedances to luminaires or lighting circuits, as previously mentioned (Fig. 16.25)
5. Ballast switching or use of multilevel ballasts (see Section 16.14)
6. Dimming by adjustment of a potentiometer at individual fixtures so equipped

Fig. 16.25 *This type of compact solid-state electronic circuit reduces ballast power input by approximately 30% and lamp output by about 28%, resulting in a net gain in efficacy. The power factor remains above 90%. Similar units are available for larger power decrease. They can be mounted on the lamp end or in the fixture channel, as shown. An ancillary benefit is cooler ballast operation, resulting in extended life. (Photo courtesy of Remtec Systems.)*

7. Replacing standard wall switches with time-out units (see Fig. 27.46), programmable units, or dimmer units

(b) Variable Time Schedule

No normal task area has a constant 24-hour, 365-day lighting requirement. In commercial and industrial spaces, work areas have regularly scheduled periods during which task lighting is not required. These include coffee and lunch breaks, cleaning periods, shift changes, and unoccupied periods. Programmed time controls can readily save 10% to 25% of the energy use, compared to relying on occupants to manually operate controls. "Tight" program scheduling takes account of lunch hour and provides after-hours lighting only in those areas actually being cleaned rather than whole floors. The payback period for the investment in control equipment varies between 1½ and 5 years. Note that static control that is insensitive to actual field conditions has only limited ability to conserve energy.

(c) Occupancy Sensing

Within a normal 9:00 A.M. to 5:00 P.M. working schedule, offices in commercial spaces are unoccupied for 30% to 60% of the time. The reasons are manifold—coffee breaks, conferences, work assignments, illness, vacations, and reassignment to a different work location are a few. Occupancy sensors can operate relays to turn off lights after a preset minimum period of about 10 minutes, or can dim the light level to a minimum in areas such as corridors, which always require some light. (They can also turn off other energy consumers such as fan-coil units, air conditioners, and fans.) Reestablishment of the original lighting level can be instantaneous, delayed, or manual on the action of the occupant. Another useful function of an occupancy sensor is to provide an automatic override in schedule systems, thus both relieving the occupant of the necessity of using a manual override and limiting the energy use to actual occupancy time. It can also light the occupant's way into a space and shut off the system after he or she has left.

Occupancy sensors that react to a human presence are of three types—passive infrared (IR), ultrasonic, and a hybrid of both technologies. The IR sensor (Fig. 16.26) reacts to the motion of a heat source within its range. It operates by creating a pattern of beams, and activates when a heat source (such as a person) moves from one beam to another. It will *not* activate to a stationary heat source. Although the IR sensor is quite sensitive, it has several disadvantages:

- Small movements may not be detected, as they may not cross from one beam (zone) to another. As a result, a person sitting quietly may not be detected and the sensor may shut down the lighting.
- Very slow movements may not be detected, even when they cross zones.
- The IR detector must "see" the heat source. Therefore, a heat source blocked by furniture will not be detected.
- The beams have a discrete width and depth. Therefore, there may be "dead" spots under the beams if the units are not carefully selected to have adequate multilevel beams, or properly located to give the desired coverage.

Ultrasonic sensors emit energy in the 25- to 40-kHz range, which is well above the range of human hearing. The waves immediately fill a space by reflecting and rereflecting off all hard surfaces, establishing a pattern that is detected by the sensor. Any movement within the space disturbs this pattern and is immediately noted by the sensor. Ultrasonic sensors have distinct advantages over IR sensors in that they do not require a direct line-of-sight exposure to the movement, and they detect small movements. The latter characteristic,

(*a*)

(*b*)

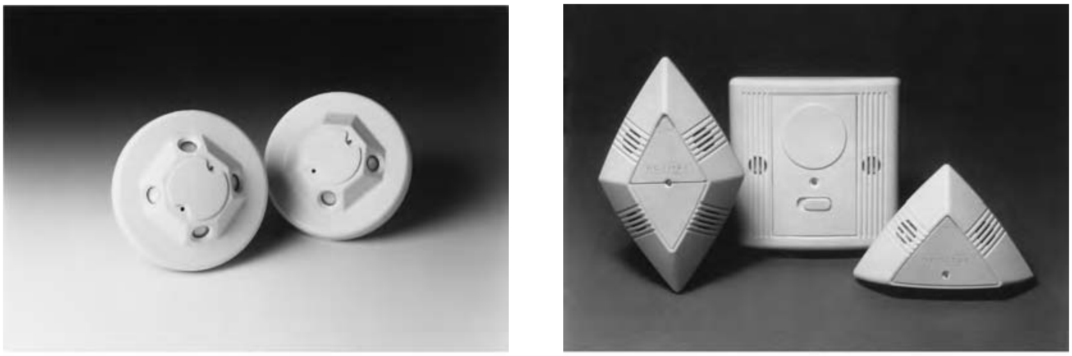
(*c*)

Fig. 16.26 *Passive infrared (PIR) occupancy sensors. All sensors can be equipped with an adjustable override to prevent turning on lighting when ambient light is sufficient. All units have adjustable delayed-off timing and a flashing LED that indicates sensor operation. (a) Flush-mounted ceiling unit. Note the 360° circular pattern of the lens, which indicates omnidirectional coverage. The unit is approximately 4 in. (100 mm) in diameter. (b) Flush-mounted combination wall switch and PIR occupancy sensor. Operation of the switch overrides the sensor function. (c) Surface-mounted wall PIR occupancy sensor. Note the semicircular shape of the lens, which indicates wide horizontal coverage. (Photos courtesy of Leviton Manufacturing Co.)*

however, is also a disadvantage inasmuch as the movement of curtains and even air movement can often trigger a sensor. It is frequently necessary to adjust (reduce) a sensor's sensitivity to avoid false sensing. Unfortunately, this also decreases its coverage.

Hybrid (dual-technology) sensors combine the characteristics of both sensor types by usually requiring both sensors to react to turn lights on, but once lights are on, a reaction in either sensor keeps them on. In addition, sophisticated electronic circuitry "learns" a space's occupancy patterns and is programmed to react accordingly.

Placement of sensors is very important and should be tested before final installation. Studies have shown that reducing the minimum "on" period below 10 minutes is counterproductive, and frequently causes space occupants to shut off the sensors. Depending on their type and mounting position, sensors cover a maximum area of 250 to 1000 ft^2 (23 to 93 m^2) per unit. The payback period for this equipment runs between 6 months and 3 years,



(a) (b)

Fig. 16.27 *Ultrasonic occupancy detectors. (a) Ceiling-mounted sensors, bidirectional on the left and unidirectional on the right. (Courtesy of Leviton Manufacturing Co.) (b) Sensors in various designs, intended for differing applications. Left to right: Ceiling-mounted two-way sensor intended for large rooms of up to 2800 ft^2 (260 m^2). Dual-function sensor and wall switch designed for rooms of up to 300 ft^2 (28 m^2); wall mounted on a single- or double-gang wall box. One-way ceiling-mounted sensor designed for use in rooms of up to approximately 1250 ft^2 (116 m^2). (Courtesy of Novitas Inc.)*

depending on the type of space and the degree of control already existing. Occupancy sensors are best applied in areas that are divided into individual rooms and work spaces. Sensors can be wall or ceiling mounted or mounted on a wall-outlet box in a combined sensor/wall-switch configuration. A few designs are shown in Fig. 16.27. (See Section 31.2, which discusses the security application of motion detectors and illustrates their operation.)

ASHRAE Standard 90.1 recognizes the great effectiveness of these devices by giving both connected power credit and a high control point equivalency.

(d) Lumen Maintenance

Referring to Section 16.20, we see that in order to maintain a minimum lighting level to the end of a maintenance period, we must deliberately overdesign initially. The extent of the overdesign is the reciprocal of the light loss factor (LLF). With a typical LLF of 0.60, this initial overdesign amounts to (1/0.60), or 66%. Assuming a linear light falloff over a 2-year maintenance period, this overdesign results in an average of 33% annual energy waste. (In the next 2-year maintenance cycle, the actual overdesign is slightly less due to a small amount of unrecoverable loss.) Because the light depreciation is a continuous and very gradual process over the maintenance period, the most appropriate control strategy is one that reduces the initial overlighting by the required amount (as measured in the field) and gradually restores it as the system ages. This control strategy, known as *lumen maintenance*, is accomplished by a dimming system operating in conjunction with local light sensors (photocells). The photocells measure ambient light, and, in response to their signals, the controller(s) operates the dimming units to raise (or lower) the light output. Depending on the size of the installation, the dimmers can either be dispersed or centralized. The modulating action of such a system over the maintenance period is shown in Fig. 16.28. This strategy, in a purely manual mode (periodic maintenance,

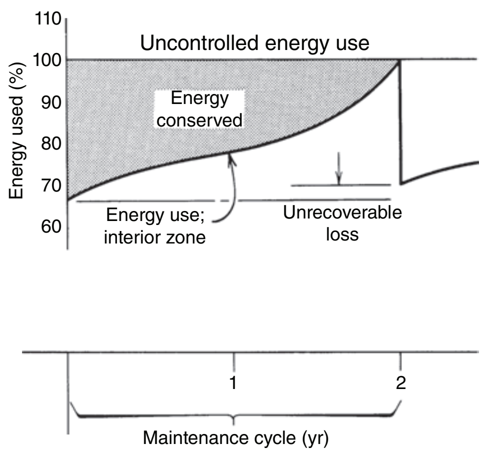


Fig. 16.28 *Graph of energy use by a system that reduces the initial lighting level to compensate for initial overdesign and gradually increases the level as system output depreciates. In subsequent cycles the energy savings are reduced slightly because of unrecoverable output loss.*

initial light reduction in accordance with the length of the maintenance period), gives only about a 10% energy reduction, whereas in an automated system almost all of the 33% annual energy waste can be eliminated.

In a new installation, the choice of whether to use electronic ballasts and full-range dimming, conventional ballasts and partial dimming, or a system of multilevel switching is an economic one and depends on many factors, one of the most important of which is the cost of energy. Often a combined system is advisable. In interior zones, initial lighting reduction does not exceed 30% to 40%, and full-range dimming is not required. In perimeter zones, daylight often provides all of the required light, and either full-range dimming, dimming plus switching, or a multilevel switching system is required (see Section 16.14 and the discussion of daylight compensation in Section 16.17*e*). The payback period for a lumen maintenance installation of this type varies from 1 to 5 years. Shorter payback periods can be obtained by using multilevel switching rather than dimming because of its lower first cost.

An additional favorable effect of initial light reduction is the lengthening of effective lamp life and a reduction in the rate of its lumen depreciation. When a lamp is operated at the rated voltage, its lumen output drops during its life (according to the type of lamp). However, if lamps are operated at reduced output, as is the case if lamps are dimmed to compensate for initial overlighting, the lamp life cycle is greatly extended, lumen depreciation is reduced, and lamp energy consumption is linearly reduced.

Typical life extension (to economic replacement) figures are:

Fluorescent	80%
Metal–halide	40%
High-pressure sodium	20%

These figures are for interior zones; for perimeter zones with ambient daylight compensation, they are higher.

(e) Daylight Compensation

A control system arranged for continuous ambient light compensation, as described in the preceding subsection, might also automatically compensate for ambient daylight. The difference is that ambient compensation for lumen maintenance due to light loss factors is a very gradual process of *increasing* output, whereas daylight compensation can be a minute-by-minute variation and generally in the direction of *decreased* electric lighting. Because of these possible rapid variations, switching systems are undesirable, as the constant on–off or level switching of lamps can be very annoying to occupants and deleterious to lamps.

Automatic dimming is the system of choice. Recognizing that in perimeter areas daylight often supplies all the required light, the system for fluorescent installations must be either full-range dimming with electronic ballasts or partial dimming with magnetic or electronic ballasts. Figure 16.29 shows the action of both types of dimming systems in a fluorescent installation with daylight compensation. The crucial design element in a daylight-compensating system is the establishment of zone areas. Depending on the latitude and climate, the southern and possibly the eastern and western exposures can have an interior (second) perimeter zone that receives sufficient daylight for a large enough portion of the year to economically warrant

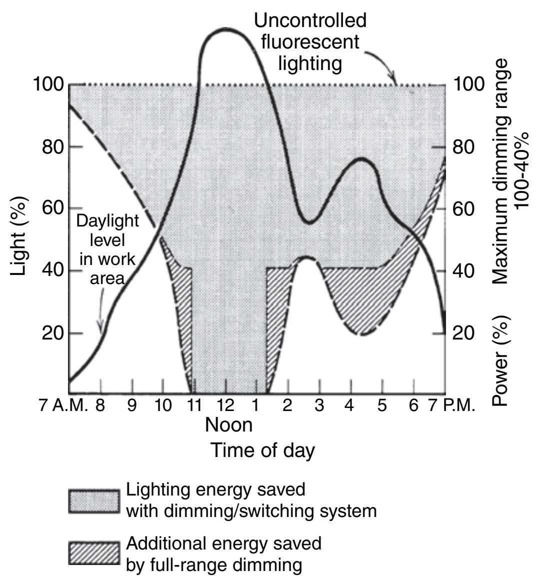


Fig. 16.29 *Typical graph of energy savings with daylight-compensating lighting control. A full-range dimming system is more effective than one that dims down to only 40%, because daylight often supplies most of the required lighting. An economic analysis is required to determine whether the additional cost of such a system is justified.*

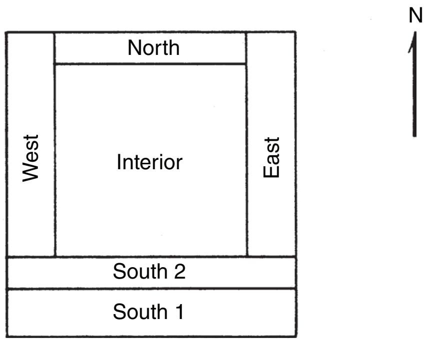


Fig. 16.30 *Typical building plan showing approximate daylight perimeter zones. Exact delineation of zones depends upon latitude, climate, window design, and cost of electric energy.*

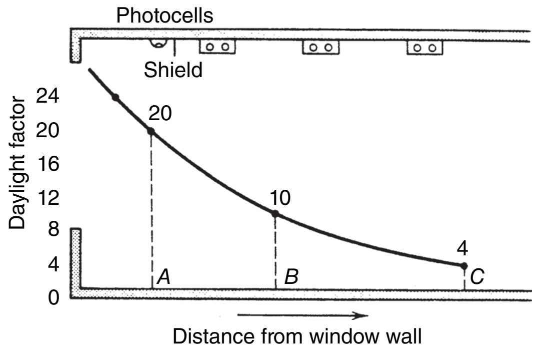


Fig. 16.31 *Typical daylight factor curve plotted on a room section with one side window. The photocell control technique for daylight compensation described in the text assumes a constant daylight factor (DF) distribution indoors—that is, fixed-luminance sky and no direct sun.*

dimming. The northern exposure has only a narrow perimeter zone (Fig. 16.30). As a starting point, the size of the zones is established by determining the maximum room depth that receives at least half of its illuminance from daylight for several hours a day. A computer daylight and dimming cost study with perimeter zone depth as a variable is an effective approach. Several such programs are available.

Placement of the control photocells depends on the control system. Where daylight compensation is desired in conjunction with lumen maintenance (see the preceding subsection), area photocells are desirable, as they give a feedback control signal for the specific area involved. Alternatively, a daylight-factor map of the space can be made—preferably after the installation is complete and the furniture in place—and photocells located at one point, based on this map (Fig. 16.31). We know from our study of daylight in Chapter 8 that the daylight factor at any inside point is constant. Therefore, by measuring actual daylight level at a point either immediately inside or outside the window, shielded from direct sun and from inside electric lighting, we can relate it to any area in the room by the ratio of daylight factors, and establish a switching level at which the lighting for that inside area is switched, partially or fully.

An example should make this clear. In Fig. 16.31, the photocells are mounted at point *A*. The ratio of daylight between points *A* and *B* is the ratio of their daylight factors—that is, 20/10, or 2.0. Therefore, if 500 lux of daylight is required at point *B* before switching lights in that area, twice that amount (2.0×500 lux) or 1000 lux is required at point *A*. Similarly, a 500-lux requirement at point *C* corresponds to (20/4)(500) or 2500 lux at point *A*. Therefore, switching can be initiated by two single-level photocells or a multilevel unit at point *A*, with settings at 1000 and 2500 lux. Other switching arrangements can be made on the same principle. Dimming initiation can also be arranged in this fashion.

Daylight compensation can reduce energy use in perimeter areas by up to 60%, depending on latitude, climate, depth of perimeter zone, hours of building use, initial power density, and so on. The amount saved for the entire building depends on the building's configuration—that is, the ratio of perimeter to total area. Payback time is usually in the range of 3 months to 3 years.

In summary, a well-designed lighting control system can provide energy conservation of up to 60%, extremely long lamp life, reduced cooling costs, extended ballast life, and reduced maintenance costs. When all these factors are considered, the investment payback period (see Appendix J) is always short and therefore financially attractive. An aspect of a centralized lighting control system not discussed previously, because it is not directly concerned with lighting, is its use in connection with peak demand reduction (see Chapter 26). When interconnected with a demand controller, this approach acts to reduce the electric lighting load in accordance with a predetermined preferential-load schedule and can achieve significant savings.

DETAILED DESIGN PROCEDURES

16.18 CALCULATION OF AVERAGE ILLUMINANCE

Once a luminaire has been selected on the basis of the foregoing criteria, all that remains is to calculate the number of such fixtures required in each space, for uniform *general* illuminance, and to arrange them properly. Although a number of calculation methods are available, the lumen (flux) method is simplest and most applicable to our need for area-lighting calculations. Illuminance calculation from point, line, or area sources is covered in Sections 16.27 to 16.30. Luminance (photometric brightness) calculations are covered in Section 16.32.

Before beginning a detailed description of the zonal cavity calculation method, a general comment on precision is in order. The precision of any calculation should not exceed either the accuracy required or the precision of available data. Thus, there is no point in working to three decimal places if a ±10% rounding of the result is common and acceptable, or if the data available are accurate to only one decimal place. As the reader will see, the lumen (lighting flux) method of *average* illuminance calculation is replete with assumptions and estimates. Among these are:

1. It is assumed that the space is empty. This is not normally the case.
2. It is assumed that all surfaces are perfect diffusers. This is not the case.
3. All surface reflectances are estimates, ±10%.
4. Maintenance conditions are estimates, at best ±10%.
5. No allowance is made for deviation of the performance of an individual product from its specification.

Any attempt to account accurately for these approximations would enormously complicate the calculation and would serve no useful purpose for this type of *average* illuminance calculation. For this reason, the procedure presented here introduces some approximations (which we feel are well justified) in the interest of simplification. These approximations are noted wherever used.

16.19 CALCULATION OF HORIZONTAL ILLUMINANCE BY THE LUMEN (FLUX) METHOD

The lumen method of calculation is a procedure for determining the *average* maintained illuminance (in footcandles or lux) on the working plane in a room. The method presupposes that luminaires will be spaced so that uniformity of illumination is provided, in order that an *average* calculation will have validity. The method is based on the definition of 1 lux of illuminance as 1 lumen incident on 1 square meter of area (1 footcandle incident on 1 square foot), that is,

$$\text{lux or (fc)} = \frac{\text{lumens}}{\text{area m}^2 \text{ or (ft}^2)}$$

As explained previously, the ratio between the lumens reaching the working plane in a specific space and the lumens generated is the coefficient of utilization, CU. Or

$$\text{lumens on the working plane} = \text{lamp lumens} \times \text{CU}$$

Therefore,

$$\text{illuminance } E = \frac{\text{lamp lumens} \times \text{CU}}{\text{area}}$$

The coefficient CU is selected from tables provided by the manufacturer of a selected luminaire by a technique known as the *zonal cavity method* (explained in Section 16.21). In the absence of specific CU data, an approximation can be made by using the generic fixture types in Table 16.1.

The illuminance figure so calculated is the *initial average* illuminance. This initial level is reduced by the effect of temperature and voltage variations, dirt accumulation on luminaires and room surfaces, lamp output depreciation, and maintenance conditions. All of these effects are cumulatively referred to as the *light loss factor* (LLF):

$$\text{maintained } E = \text{initial } E \times \text{LLF}$$

(This factor was previously termed the *maintenance factor*, MF.) The procedure required to arrive at this factor is explained in the following section.

Our final expression for maintained illuminance E as calculated by the lumen method is, therefore,

$$E = \frac{\text{lamp lumens} \times \text{CU} \times \text{LLF}}{\text{area}} \tag{16.1}$$

where E is lux if area is expressed in square meters, or footcandles if the area is in square feet.

Lamp lumens is the total within the space and is equal to

$$\text{number of fixtures} \times \text{lamps per fixture} \times \text{initial lumens per lamp}$$

The formula then becomes

$$E = \frac{\text{number of luminaires} \times \text{lamps/luminaire} \times \text{lumens/lamp} \times \text{CU} \times \text{LLF}}{\text{area}} \tag{16.2}$$

or, conversely, solving for the number of luminaires required to achieve a target maintained illuminance E:

$$\text{number of luminaires} = \frac{E \times \text{area}}{\text{lamps per luminaire} \times \text{lumens per lamp} \times \text{CU} \times \text{LLF}} \tag{16.3}$$

For large areas, a much more useful figure is the area illuminated per luminaire:

$$\text{area per luminaire} = \frac{\text{lamps per luminaire} \times \text{lumens per lamp} \times \text{CU} \times \text{LLF}}{E} \tag{16.4}$$

For instance, it is much more convenient to know that to maintain, say, 60 fc within a space with a given luminaire, 70 ft^2 (6.5 m^2) per unit is appropriate than it is to know that for an 18,000-ft^2 (1672-m^2) floor, 257 fixtures are necessary. The former figure allows us to establish a pattern, say 7 × 10; the latter figure is too large to be immediately useful. Therefore, for rooms requiring more than a small number of luminaires, the latter calculation should always be used.

16.20 CALCULATION OF LIGHT LOSS FACTOR

The light loss factor (LLF) is composed of elements that can be categorized as *recoverable* and *nonrecoverable*. The former can be improved by maintenance; the latter cannot. The total LLF is the product of all the individual factors. The overview that follows includes approximations. For more precise data, see the *IESNA Lighting Handbook* (2011).

Among the nonrecoverable loss factors are the following:

(a) Luminaire Ambient Temperature

Light output changes when a *fluorescent* fixture operates at other than its design temperature. With normal indoor installation, use 1.0—that is, no depreciation. For other conditions, refer to technical data on the luminaire involved.

(b) Voltage

When a lamp operates at the rated voltage, use 1.0. Details of lamp sensitivity to voltage are given in Chapter 14.

(c) Luminaire Surface Depreciation

This factor is proportional to age and depends upon the type of surface involved. The designer must estimate this factor based on knowledge of the luminaire materials.

(d) Components

Losses due to components include ballast factor, ballast-lamp photometric factor, equipment operating factor, and lamp position (tilt) factor. Air troffers also introduce a thermal factor. In the absence of specific data for component factors, use a total of 0.92.

In the absence of reliable data for any of the foregoing nonrecoverable factors, use an overall factor representing the product $a \times b \times c \times d$ of 0.88.

The factors that follow are *recoverable*—that is, they can be returned to their initial state by maintenance.

(e) Room Surface Dirt

This factor is self-explanatory. Lighting approaches that depend heavily on surface reflections, such as indirect systems, are more seriously affected than systems that deliver most of their useful light directly. Assuming a 24-month cleaning cycle and normal conditions of cleanliness, use the appropriate factor in the following list. Alter it for other conditions such as infrequent maintenance and unusual cleanliness or dirtiness.

Direct lighting: 0.92 ± 5%
Semi-direct lighting: 0.87 ± 8%
Direct–indirect lighting: 0.82 ± 10%
Semi-indirect lighting: 0.77 ± 12%
Indirect lighting: 0.72 ± 17%

(f) Lamp Lumen Depreciation

This factor depends upon the type of lamp and the replacement schedule. Use the following when exact data are unavailable:

	Group Replacement	Replacement on Burnout
Incandescent	0.94	0.88
Tungsten–halogen	0.98	0.94
Fluorescent	0.90	0.85
Mercury-vapor	0.82	0.74
Metal–halide	0.87	0.80
High-pressure sodium	0.94	0.88

(g) Burnouts

This factor accounts for lamps that produce no output but have not been replaced. It depends upon maintenance schedules and method of replacement. Use the following as a general rule:

Group replacement procedures: 1.0

Individual replacement on burnout: 0.95

(h) Luminaire Dirt Depreciation

The luminaire dirt depreciation (LDD) factor depends upon luminaire design, atmosphere conditions in the space, and maintenance schedule. The luminaire maintenance category is obtained from the manufacturer's data or from Table 16.1. The type of atmosphere is determined by considering the space involved. Assuming a 12-month cleaning schedule and normal room cleanliness, use the base number in Fig. 16.32 and change it to match the conditions of dirt and maintenance. The categories correspond to those used by the IESNA.

Total LLF is the product of all the depreciation factors:

$$\text{LLF} = a \times b \times c \times d \times e \times f \times g \times h$$

For example, a fluorescent air troffer in a regularly maintained group-lamp-replacement, air-conditioned office might typically have an LLF of 0.8. The same fixture in the same office, but with walls and fixture cleaned only when burned-out lamps are replaced, would typically have an LLF of 0.55. Thus, if in the first case the maintained illumination is E fc, in the second case it is 0.55/0.80 or 0.69 E fc, that is, a reduction of 31% as a result of poor maintenance. When a detailed determination of LLF is not possible, use the factors given in Section 16.22 (they are somewhat conservative).

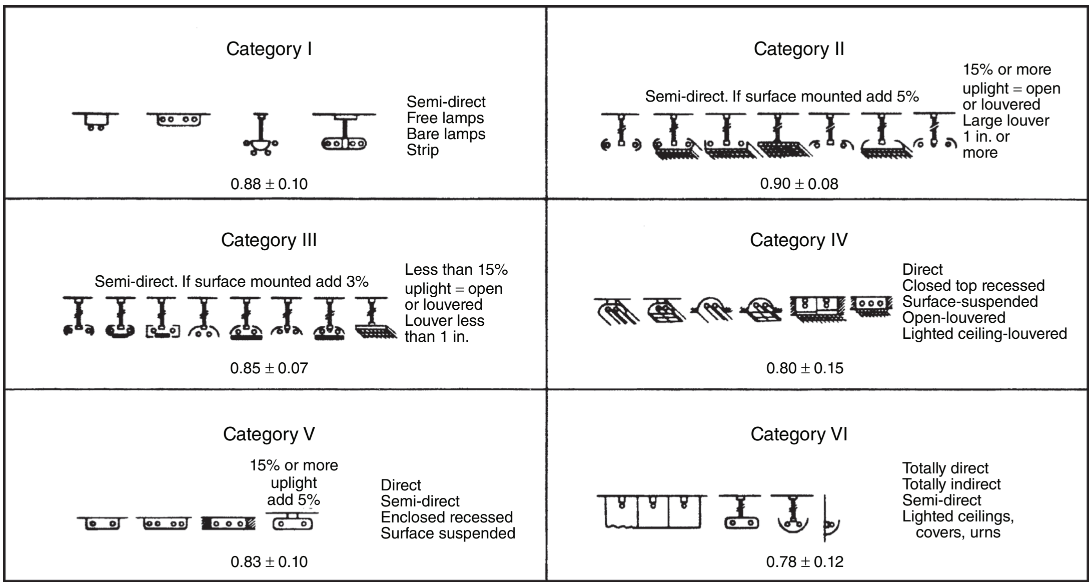


Fig. 16.32 *The LDD factor is determined from the category of luminaire (which is an indication of its proneness to dirt accumulation) plus knowledge of room ambient conditions.*

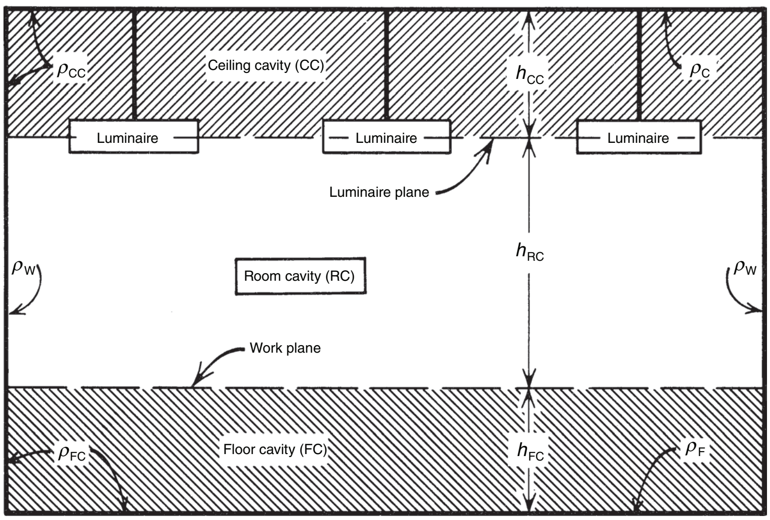
16.21 DETERMINATION OF THE COEFFICIENT OF UTILIZATION BY THE ZONAL CAVITY METHOD

The coefficient of utilization (CU) connects a particular fixture to a particular space by relating the luminaire's light distribution characteristic to the room's size and its surface reflectances. To account for the luminaire's mounting height and its relationship to the working plane, the space is divided into three cavities: a ceiling cavity above the fixture, a floor cavity below the working plane, and a room cavity between the two (Fig. 16.33). Given the surface reflectances, the effective reflectances of the floor and ceiling cavities can be obtained. With these, the CU can be selected from tables (either Table 16.1 or from manufacturer's data) and the lumen formula (Equation 16.3) applied to arrive at average illuminance. A step-by-step explanation of the method plus illustrative examples demonstrate the procedure. The reader should follow the steps with the flow chart in Fig. 16.34 and the calculation form in Fig. 16.35 in hand.

STEP 1. First, dimensional data are established. In offices, schools, and many other occupancies, the work plane is 30 in. (760 mm) above the finished floor (AFF). In drafting rooms it is 36 to 38 in. (915 to 965 mm); in shops, 42 to 48 in. (1066 to 1220 mm); in carpet stores and sail-cutting rooms at floor level. The three *h* terms are the heights of the various cavities. Also identify the initial reflectance of the room surfaces and fill in the sketch in Fig. 16.35. Utilize the reflectance closest to those given in Table 16.2.

STEP 2. See Fig. 16.35. This step involves determining the cavity ratios of the room by calculation. The basic expression for a cavity ratio (CR) is

$$CR = 2.5 \times \frac{\text{area of cavity wall}}{\text{area of work plane}} \qquad (16.5)$$



Legend:
ρ_C = ceiling reflectance
ρ_{CC} = ceiling cavity reflectance
ρ_W = wall reflectance
ρ_F = floor reflectance
ρ_{FC} = floor cavity reflectance
h = height in feet or meters
h_{RC} = height of room cavity (etc.)

Fig. 16.33 *Room cavities as used in the zonal cavity method.*

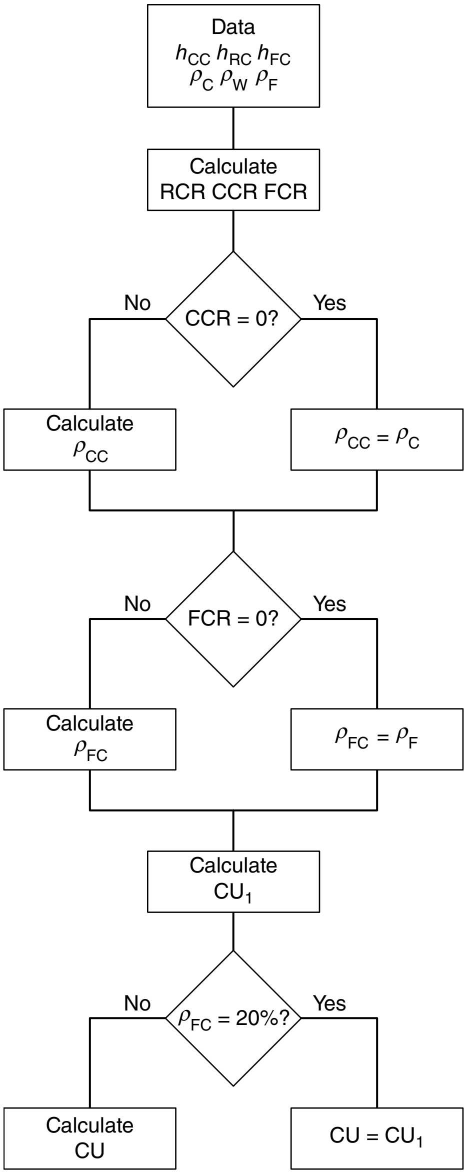


Fig. 16.34 *Zonal cavity method flow chart.*

In a rectangular space, the area of the cavity wall is $h \times (2l \times 2w)$ or $2h(l + w)$; therefore,

$$\mathrm{CR} = \frac{2.5 \times 2h(l + w)}{\text{area of work plane}}$$

or

$$\mathrm{CR} = 5h \times \frac{l + w}{l \times w} \tag{16.6}$$

For other than rectangular rooms, the area can be calculated as required by geometry. For instance, in a circular room, the cavity wall area = $h \times 2\pi r$ and the work plane area is πr^2. Thus,

$$\mathrm{CR} = \frac{2.5 \times h \times 2\pi\, r}{\pi\, r^2} = \frac{5h}{r} \tag{16.7}$$

For each of the cavities in a rectangular room we have:

Room cavity ratio

$$\mathrm{RCR} = 5h_{RC}\frac{l + w}{l \times w} \tag{16.8}$$

Ceiling cavity ratio

$$\mathrm{CCR} = 5h_{CC}\frac{l + w}{l \times w} \tag{16.9}$$

Floor cavity ratio

$$\mathrm{FCR} = 5h_{FC}\frac{l + w}{l \times w} \tag{16.10}$$

For reference, because CR values for a space are related, once one has been determined, the others can be obtained by ratios

$$\mathrm{CCR} = \mathrm{RCR}\frac{h_{CC}}{h_{RC}} \tag{16.11}$$

$$\mathrm{FCR} = \mathrm{RCR}\frac{h_{FC}}{h_{RC}} \tag{16.12}$$

and

$$\mathrm{CCR} = \mathrm{FCR}\frac{h_{CC}}{h_{FC}} \tag{16.13}$$

STEP 3. See Table 16.2 and Figs. 16.34 and 16.35. This step involves obtaining the effective ceiling cavity reflectance (ρ_{FC}) from Table 16.2. Note that the wall reflectance remains as selected in step 1. If the fixtures are surface-mounted or recessed, then CCR = 0 and ρ_{CC} = selected ceiling surface reflectance.

STEP 4. See Table 16.2 and Figs. 16.34 and 16.35. This step involves obtaining the effective floor cavity reflectance ρ_{FC}, as in step 3 for ρ_{CC}. If the floor is the working plane, FCR = 0 and ρ_{FC} = selected floor surface reflectance.

STEP 5. Select the CU from the manufacturer's data. Note that interpolation may be necessary for CCR (ρ_{CC}) if it is between the figures in the CU table. See Example 16.1 in the next section. CU correction factors for ρ_{FC} other than 20% (the standard value in CU tables) are given in Table 16.3.

GENERAL INFORMATION

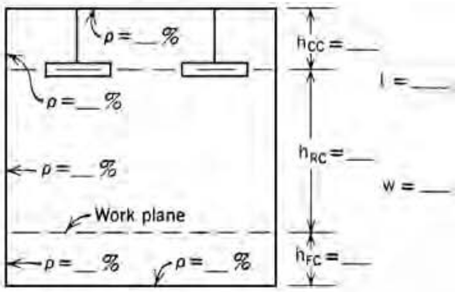
1. Project identification: ______________________________
(Give name of area and/or building and room number)

2. Average maintained illumination for design: ______ lux [footcandles]

Luminaire data:
3. Manufacturer: ______________________
4. Catalog number: ______________________

Lamp data:
5. Type and color: ______________________
6. Number per luminaire: ______________________
7. Total lumens per luminaire: ______________________

SELECTION OF COEFFICIENT OF UTILIZATION



8. Step 1: Fill in sketch at right.

9. Step 2: Determine Cavity Ratios by formulas.

9a. Room cavity ratio, RCR = ______________________
9b. Ceiling cavity ratio, CCR = ______________________
9c. Floor cavity ratio, FCR = ______________________

10. Step 3: Obtain effective ceiling cavity reflectance (ρ_{CC}) from Table 16.2. ρ_{CC} = ______

11. Step 4: Obtain effective floor cavity reflectance (ρ_{FC}) from Table 16.2. ρ_{FC} = ______

12. Step 5: Obtain coefficient of utilization (CU) from manufacturer's data. CU = ______

SELECTION OF LIGHT LOSS FACTORS

Unrecoverable
13. Luminaire ambient temperature ______
14. Voltage to luminaire ______
15. Luminaire surface depreciation ______
16. Other factors **(components)** ______

Recoverable
17. Room surface dirt depreciation ______
18. Lamp lumen depreciation ______
19. Lamp burnouts factor ______
20. Luminaire dirt depreciation LDD ______

21. Total light loss factor, LLF (product of individual factors above): ______

CALCULATIONS

(Average maintained illumination level)

$$\text{Number of luminaires} = \frac{(\text{Illuminance}) \times (\text{Area})}{(\text{Lumens per luminaire}) \times (\text{CU}) \times (\text{LLF})}$$

22. $= \frac{\qquad\qquad}{\qquad\qquad} =$

$$\text{Lux [footcandles]} = \frac{(\text{number of luminaires}) \times (\text{lumens per luminaire}) \times (\text{CU}) \times (\text{LLF})}{(\text{area})}$$

23. $= \frac{\qquad\qquad}{\qquad\qquad} =$

24. Calculated by: ______________________ Date: ______

Interactive Animation

Fig. 16.35 *Zonal cavity method calculation form. (Courtesy of IESNA.)*

TABLE 16.2 Percent Effective Ceiling or Floor Cavity Reflectance (ρ_{CC}, ρ_{FC}) for Various Reflectance Combinations

Percent Ceiling ρ_C or Floor Reflectance ρ_F:	90				80				70			50			30				10		
Percent Wall Reflectance ρ_W:	**90**	**70**	**50**	**30**	**80**	**70**	**50**	**30**	**70**	**50**	**30**	**70**	**50**	**30**	**65**	**50**	**30**	**10**	**50**	**30**	**10**
Ceiling or Floor Cavity Ratios—CCR or FCR 0	90	90	90	90	80	80	80	80	70	70	70	50	50	50	30	30	30	30	10	10	10
0.2	89	88	86	85	79	78	77	76	68	67	66	49	48	47	30	29	29	28	10	10	9
0.4	88	86	83	81	78	76	74	72	67	65	63	48	46	45	30	29	27	26	11	10	9
0.6	88	84	80	76	77	75	71	68	65	62	59	47	45	43	29	28	26	25	11	10	9
0.8	87	82	77	73	75	73	69	65	64	60	56	47	43	41	29	27	25	23	11	10	8
1.0	86	80	74	69	74	71	66	61	63	58	53	46	42	39	29	27	24	22	11	9	8
1.2	86	78	72	65	73	70	64	58	61	56	50	45	41	37	29	26	23	20	12	9	7
1.4	85	77	69	62	72	68	62	55	60	54	48	45	40	35	28	26	22	19	12	9	7
1.6	85	75	66	59	71	67	60	53	59	52	45	44	39	33	28	25	21	18	12	9	7
1.8	84	73	64	56	70	65	58	50	57	50	43	43	37	32	28	25	21	17	12	9	6
2.0	83	72	62	53	69	64	56	48	56	48	41	43	37	30	28	24	20	16	12	9	6
2.2	83	70	60	51	68	63	54	45	55	46	39	42	36	29	28	24	19	15	13	9	6
2.4	82	68	58	48	67	61	52	43	54	45	37	42	35	27	28	24	19	14	13	9	6
2.6	82	67	56	46	66	60	50	41	53	43	35	41	34	26	27	23	18	13	13	9	5
2.8	81	66	54	44	66	59	48	39	52	42	33	41	33	25	27	23	18	13	13	9	5
3.0	81	64	52	42	65	58	47	38	51	40	32	40	32	24	27	22	17	12	13	8	5
3.5	79	61	48	37	63	55	43	33	48	38	29	39	30	22	26	22	16	11	13	8	5
4.0	78	58	44	33	61	52	40	30	46	35	26	38	29	20	26	21	15	9	13	8	4
4.5	77	55	41	30	59	50	37	27	45	33	24	37	27	19	25	20	14	8	14	8	4
5.0	76	53	38	27	57	48	35	25	43	32	22	36	26	17	25	19	13	7	14	8	4

Source: Extracted from the *IESNA Lighting Handbook* (1993); reprinted with permission. For more complete data, see the current *IESNA Lighting Handbook.*

TABLE 16.3 CU Adjustment Factors for Effective Floor Cavity Reflectances Other Than 20% (Any Wall Reflectance)[a]

For 30% effective floor cavity reflectance, *multiply* standard CU value by the appropriate factor from the following table. For 10% effective floor cavity reflectance, *divide* standard CU value by the appropriate factor from the following table.

	Percent Effective Ceiling Cavity Reflectance, ρ_{CC}			
Room Cavity Ratio	**80**	**70**	**50**	**10**
1	1.08	1.06	1.04	1.01
2	1.06	1.05	1.03	1.01
3	1.04	1.04	1.03	1.01
4	1.03	1.03	1.02	1.01
5	1.03	1.02	1.02	1.01
6	1.02	1.02	1.02	1.01
7	1.02	1.02	1.01	1.01
8	1.02	1.02	1.01	1.01
9	1.01	1.01	1.01	1.01
10	1.01	1.01	1.01	1.01

Source: Extracted from the *IESNA Lighting Handbook* (1993); reprinted with permission.

[a]For more precise data, for varying ρ_W, see the current *IESNA Lighting Handbook.*

STEP 6. Calculate the illuminance and the number of fixtures or area per luminaire as in Section 16.19.

Illustrative examples and shortcut methods are demonstrated in the following section. CU coefficients are listed in Table 16.1 for generic luminaire types.

16.22 ZONAL CAVITY CALCULATIONS: ILLUSTRATIVE EXAMPLES

EXAMPLE 16.1 It is suggested that the reader photocopy Fig. 16.35 and fill it in as the solution to this example is developed.

Given. Assume a classroom with dimensions of (W × L × H): 6 m × 8 m × 3.7 m (19.7 × 26.3 × 12.1 ft), at an elementary school. Initial reflectances are: ceiling 80%, entire wall 50%, floor 20%. (Note that the sketch in Fig. 16.35 can accommodate different reflectances for the upper, center, and lower wall sections.) The goal is to provide adequate illuminance using fluorescent fixtures. Assume yearly maintenance, lamp replacement at burnout, proper voltage and ballasts, and a medium clean atmosphere.

SOLUTION

(*a) Illuminance target.* Referring to tables in the IESNA *Lighting Handbook*, find the recommended illuminance target (for this example 500 lux). The daylight contribution in much of the space is usually considerable because of the hours of use. It frequently exceeds this 500-lux target, but to demonstrate the calculation procedure, we assume an absence of daylight. Lines 1, 2, and 8 (room sketch) of Fig. 16.35 can be filled in.

(*b) Luminaire selection.* The criteria we have previously developed for a classroom situation require an installation that yields:

1. Low direct glare (high VCP) because schoolchildren spend a large proportion of their time in a heads-up position
2. Low veiling reflections because much of the seeing task involves high-reflectance materials, occasionally specular
3. High efficiency and low energy use to meet ANSI/ASHRAE/IESNA Standard 90.1 and most governmental requirements
4. Minimum required maintenance in view of the poor cleaning and maintenance situation that exists in many schools

Although the ceiling height is sufficient to permit use of indirect lighting (e.g., luminaire 33 in Table 16.1) with all of its distinct advantages, it is not chosen because:

5. The luminaire maintenance category is inappropriate, and given the type of maintenance expected, light reduction would be serious.
6. Indirect lighting depends on a highly reflective ceiling, requiring yearly cleaning and repainting at intervals not exceeding 5 years. This is not generally the case in public schools.

As a result, we select a two-lamp version of luminaire No. 44 from Table 16.1. This unit is a parabolic aluminum reflector with louvers and exhibits a 45° cutoff and a crosswise batwing distribution. (Fig. 16.14 shows a unit of this design.) This fixture meets requirements 1 through 4.

Although its distribution curve (see Table 16.1) shows no upward component, most commercial units of this basic design do have slots in the top of the reflector and show 5% to 10% uplight. In practice, we would select such a unit. This avoids an excessively dark ceiling and undesirable luminance ratios between fixture and background. Furthermore, fixtures with top slots stay cleaner because of the upward air movement through the fixture caused by the warm lamps and ballast. The mounting height should be about 2.7 m (9 ft) to permit easy maintenance and good row spacing. For this luminaire the recommended maximum SC can be estimated at between 1.5 and 2.0. The work plane height is 750 mm (30 in.).

(*c)* Calculations.

STEP 1. The required data that should appear in the sketch in Fig. 16.35 are

$h_{CC} = 1.0$ m	$h_{RC} = 1.95$ m
$h_{FC} = 0.75$ m	$l = 8$ m
$\rho_C = 80\%$	$\rho_W = 50\%$
$\rho_F = 20\%$	$w = 6$ m

STEP 2. From Equations 16.8, 16.9, and 16.10

$$\frac{l + w}{l \times w} = 0.29$$

$$\text{RCR} = 5h_{RC}\frac{l + w}{l \times w}$$

$$\text{RCR} = 5\,(1.95)(0.29) = 2.84$$
$$\text{CCR} = 5\,(1)(0.29) = 1.46$$
$$\text{FCR} = 5\,(0.75)(0.29) = 1.09$$

STEP 3. From Table 16.2 obtain effective reflectances: For ρ_{CC} use $\rho_C = 0.8$, $\rho_W = 0.5$, and CCR = 1.46. Therefore,

$$\rho_{CC} = 0.61$$

STEP 4. For ρ_{FC} use $\rho_F = 0.2$, $\rho_W = 0.5$, and FCR = 1.09. Therefore,

$$\rho_{FC} = 0.18 \text{ by interpolation}$$

STEP 5. Interpolation between RCR of 2.8 and 3.0 is necessary. The CU for the selected luminaire—No. 44 of Table 16.1—can now be obtained by double interpolation.

ρ**w = 0.50**	**CU**		
ρ**CC** →	**0.70**	**0.61**	**0.50**
RCR			
2.0	0.58		0.55
2.84		?	
3.0	0.52		0.50

Design CU = 0.52. No correction from Table 16.3 is required, as ρ_{FC} is close to 20%. At this stage, lines 9 through 12 of Fig. 16.35 can be filled in.

STEP 6. The LLF (see Section 16.20) results from establishing items 13 to 20 of Fig. 16.35. These are:

Items 13–16	0.88
Item 17	0.95
Item 18	0.85
Item 19	0.95
Item 20	0.80

Item 21: LLF = (0.88)(0.95)(0.85)(0.95)(0.80) = 0.54

STEP 7. Lumen calculation. A typical classroom is normally divided into a large student seating area and a teacher's area. The illuminance requirement is approximately the same for both, so the room can be treated as a single unit for visual task purposes. A good lighting design includes chalkboard lighting, the spill light from which is usually sufficient to illuminate the front of the room. Treating the entire space as one visual task area, and assuming two nominal 40-W, 4100 K fluorescent lamps per fixture, the number N of luminaires required is, from Equation 16.3,

$$N = \frac{(500 \text{ lux})(6 \times 8 \text{ m})}{2(3200 \text{ lm})(0.52)(0.54)} = 13.35$$

The remaining lines of Fig. 16.35 can now be completed.

Refer now to Fig. 16.36 for the layout. Two lengthwise rows of fixtures, spaced 300 cm apart, give excellent coverage, as shown. The resultant spacing-to-mounting-height ratio

$$\frac{300 \text{ cm spacing}}{270 \text{ cm mounting height}} = 1.1$$

is well below the maximum of 1.5 to 2.0 estimated by inspection of the candlepower distribution curve. The sixth fixture in the outside (window) row provides illumination for the teacher's desk. Two *single-lamp* batwing distribution or asymmetric distribution luminaires provide chalkboard and front-of-room lighting. The window wall row is separately switched and is farther from the wall than the inside row due to the usual presence of daylight. Point-by-point illuminance can be computed by one of the available computer programs. The daylight contribution can also be included. Actual *average* illuminance in the room would be simply the ratio of the number of fixtures used to the number required (calculated) times the target illuminance:

$$E = \frac{11 + \frac{1}{2} + \frac{1}{2}}{13.35}(500 \text{ lux}) = 450 \text{ lux}$$

assuming similar characteristics for the one- and two-lamp fixtures. The designer must decide if this illuminance is appropriately close to the 500 lux target illuminance. ■

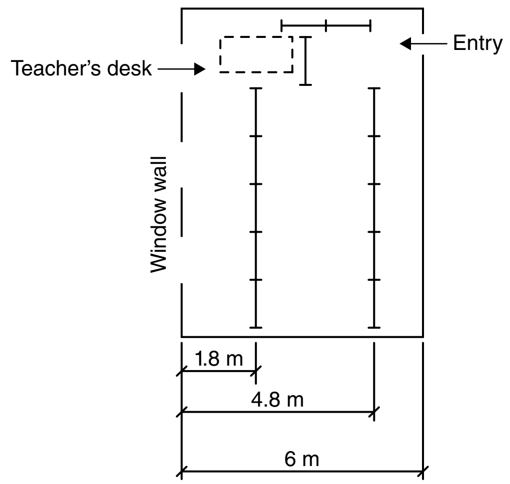


Fig. 16.36 *Layout of pendant parabolic aluminum reflector luminaires in a typical classroom. The units have a modified batwing distribution in the crosswise direction, which mandates their being hung with their long axis parallel to the line of sight, as shown. Furthermore, the fixtures have lower brightness in that direction, that is, VCP for students in the head-up position is excellent. Note that the distance between the outside fixture row and the window wall is more than one-half of the side-to-side spacing because of daylight contribution during school hours, whereas the inside fixture row to inside wall spacing is less than one-half of the side-to-side spacing in order to maintain sufficient illuminance near that wall. The single fixture to the right of the teacher's desk (to the teacher's left) was so placed to avoid the veiling reflections that would result from a fixture directly above the desk and to take advantage of the fixture's transverse batwing distribution characteristic.*

EXAMPLE 16.2 Assume a large modern business office, with dimensions of (L × W × hung ceiling H) 60 ft × 100 ft × 8 ft (18 × 30 × 2.4 m). Initial reflectances are 0.80, 0.50, and 0.30. Provide general lighting using fluorescent lamps with high-efficiency ballasts in recessed troffer luminaires. The space is fully air-conditioned. Lamps are replaced on a burnout basis, and the fixture is then cleaned.

SOLUTION

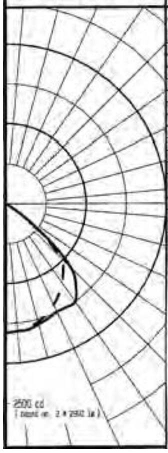
Luminaires with parabolic diffusers, reflectors, and/or baffles, which exhibit very low high-angle luminance, meet this requirement, as explained in Section 16.4.

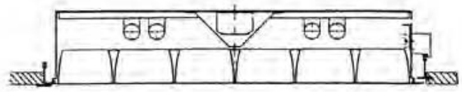
A second consideration is that in an office of this size, which may well be "landscaped" using half-height partitions, viewing directions vary greatly, negating any benefits inherent in a luminaire's directionality. As a result, we selected a specular parabolic baffled 2-ft (610-mm) unit, which is

REK D/RIK-D 2/31-U

Recessed mounted luminaire with parabolic mirrored louver (without mirrored reflector)

Shielding angle : Parl.: 60 - Norm.: 60





CANDLEPOWER DEG.	Parl.	22.5	45	67.5	Norm.	Flux
0	1609	1609	1609	1609	1609	
5	1603	1603	1607	1608	1605	177
10	1577	1579	1589	1598	1600	
15	1534	1534	1551	1565	1584	506
20	1473	1480	1490	1522	1528	
25	1400	1412	1431	1481	1498	773
30	1312	1327	1365	1464	1502	
35	1212	1235	1311	1448	1501	964
40	1102	1141	1263	1328	1352	
45	970	1034	1138	1135	1149	892
50	599	572	617	621	635	
56	122	129	139	140	144	223
60	14	14	15	15	16	
65	12	5	11	7	10	10
70	3	3	2	3	4	
75	2	2	1	2	2	2
80	2	1	1	1	2	
85	1	1	1	2	2	2
90	2	2	2	2	2	
95	0	0	0	0	0	0
100-180	0	0	0	0	0	

COEFFICIENTS OF UTILIZATION

LUMINAIRE EFFICIENCY : 0.61

REFL. FACT. CEILING	80			70			50			30			10			0
WALLS	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	0
FLOOR	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
ROOM CAVITY RATIO – RCR 1	64	61	59	62	60	58	60	58	56	57	56	54	55	54	53	52
2	57	54	51	56	53	50	54	51	49	52	50	48	50	48	47	45
3	53	49	46	53	49	46	51	48	45	49	47	44	48	45	44	42
4	49	45	42	49	45	41	47	44	41	46	43	40	45	42	40	39
5	45	41	38	45	41	37	44	40	37	42	39	37	41	39	36	35
6	42	37	34	41	37	34	40	35	33	39	36	33	38	35	33	32
7	38	34	30	38	33	30	37	33	30	36	33	30	35	32	30	29
8	35	31	28	35	31	28	34	30	27	33	30	27	33	30	27	26
9	33	29	26	33	28	26	32	28	25	31	28	25	31	28	25	24
10	30	26	23	30	26	23	30	26	23	29	26	23	29	25	23	22

ZONAL SUMMARY ZONE	LUMENS	LAMP	FIXT	AVG [cd/m²] DEG.	NORM.	45°	PARL.
0 - 30	1456	25.1	41.0	45	5091	5041	4296
0 - 40	2420	41.7	68.2	50	3092	3009	2624
0 - 50	3312	57.1	93.3	55	766	759	665
0 - 60	3535	61.0	99.6	60	98	94	85
0 - 70	3545	61.1	99.9	65	75	81	86
0 - 90	3549	61.2	100.0	70	35	16	24
90 - 180	0	0.0	0.0	75	28	14	21
0 - 180	3550	61.2	100.0	80	31	21	31

Fig. 16.37 *Complete photometric data on a 2-ft (610-mm) square fixture with a 36-cell mirrored parabolic louver. The unit uses two T8 U-shaped 32-W fluorescent lamps. Note that the transverse distribution characteristic has a modified batwing shape typical of this type of louver. The louver's specular finish yields very low brightness at high angles, as can be seen from both the distribution curve and the luminance (cd/m²) data. (Courtesy of Zumtobel-STAFF.)*

directionally and architecturally neutral and displays the required low levels of luminance at high angles. The unit's characteristics, when equipped with two 32-W, T8, U-shaped lamps with 2800 initial lumens, are given in Fig. 16.37. Note that the luminaire exhibits a modified batwing intensity distribution in the transverse direction.

Calculations. The reader should fill in a copy of Fig. 16.35 as we proceed. The working plane is taken as the desktop height (i.e., 30 in. or 2.5 ft).

STEP 1. $h_{CC} = 0$; $h_{RC} = 5.5$; $h_{FC} = 2.5$.

STEP 2. CCR = 0; RCR = 0.73; FCR = 0.33.

STEP 3. ρ_W = 50%; ρ_{CC} = 80% (for a recessed fixture we use the ceiling reflectance).

STEP 4. From Table 16.2, ρ_{FC} = 29%.

STEP 5. We find CU for ρ_{FC} = 20% by extrapolation:

RCR	CU	
0.73	?	
1.0	0.64	CU = 0.66
2.0	0.57	

STEP 6. From Table 16.3, the multiplier for ρ_{FC} = 30% (close to 29%) is 1.085.

STEP 7. Final CU = 1.085 (0.66) = 0.72.

STEP 8. LLF per Fig. 16.35:

1.0	0.92	
1.0	0.85	
0.9	0.95	LLF = 0.54
0.92	0.88	

STEP 9.

$$\text{area/luminaire} = \frac{\text{lamps} \times \text{lumens/lamp} \times \text{CU} \times \text{LLF}}{\text{illuminance}}$$

$$= \frac{2(2800)(0.72)(0.54)}{500\,/\,10.76 \text{ lux per fc}} = 47 \text{ ft}^2$$

With mounting height 5.5 ft (1.7 m) above the working plane, estimated spacing criteria of 1.8 transverse and 1.2 parallel yield maxima of 9.9 ft (3 m) transverse and 6.6 ft (2 m) parallel for fixture centerlines. We would test grids of 9 ft × 5 ft (2.7 m

× 1.5 m) and 8 ft × 6 ft (2.4 m × 1.8 m) using computer software to see which yielded better results for uniformity of illumination and lower reflected glare in *all* directions, because, as noted previously, viewing directions will probably vary. In the absence of appropriate software, we would select a 9 ft × 6 ft (2.7 m × 1.8 m) grid to take advantage of the batwing characteristic. Note the important fact that a maintained level of 500 lux (50 fc) of high-quality illuminance for digital display areas is achieved with a power density of less than 1.6 W/ft^2 (17.54 W/m^2). ■

16.23 ZONAL CAVITY CALCULATION BY APPROXIMATION

Although the foregoing zonal cavity calculations are straightforward and essentially simple, they can become tedious if more than a few areas are involved. Two alternatives exist: to utilize one of the many computer programs available, or simply to shorten the calculations with reasonable approximations. Computer assistance is discussed in Sections 16.30 and 16.31 and Appendix L. An effective computational method using approximations is demonstrated in this section, which is based upon a method developed by B. F. Jones.

Fill in the calculation sheet for illuminance calculation by approximation, as shown in Figure 16.38. Assume that all rooms are square. To do this for a rectangle, take one-third of the difference in dimensions and add to the smaller dimension to obtain the equivalent width w. Then, for square rooms

$$\mathrm{RCR} = \frac{10h_{RC}}{w}$$

Then, using the calculated side dimension of the square equivalent room, assume:

1. $\rho_{CC} = 0.80$ for a large room, that is, equal to or larger than 30 × 30 ft (10 × 10 m).
   $\rho_{CC} = 0.70$ for a medium room, that is, between 30 × 30 ft (10 × 10 m) and 12 × 12 ft (4 × 4 m).
   $\rho_{CC} = 0.60$ for a small room, that is, equal to or smaller than 12 × 12 ft (4 × 4 m).
2. Assume that $\rho_{FC} = 0.20$.
3. Assume that LLF = 0.65 for good conditions, 0.55 for average conditions, and 0.45 for poor conditions.

EXAMPLE 16.3 Classroom as in Example 16.1 by approximation.

1. "Square" the room.

$$w_{SQ} = 6 + \frac{8-6}{3} = 6\tfrac{2}{3}$$

2. Assume

$$\rho_{CC} = 70;\ \rho_{W} = 50;\ \rho_{FC} = 20$$

3. Calculate RCR

$$\mathrm{RCR} = \frac{10 \times 1.95}{6\tfrac{2}{3}} = \frac{19.5}{6.66} = 2.93$$

4. Obtain CU from Table 16.1, fixture No. 44. CU = 0.52 by visual inspection.
5. Calculate fixtures

$$N = \frac{500(6 \times 8\ \mathrm{m})}{2(3200)(0.52)(0.55)}$$
$$= 13.11\ \text{fixtures}$$

Thus, the result is substantially the same as the accurate calculation. Let us also check Example 16.2. ■

EXAMPLE 16.4 Office as in Example 16.2 by approximation.

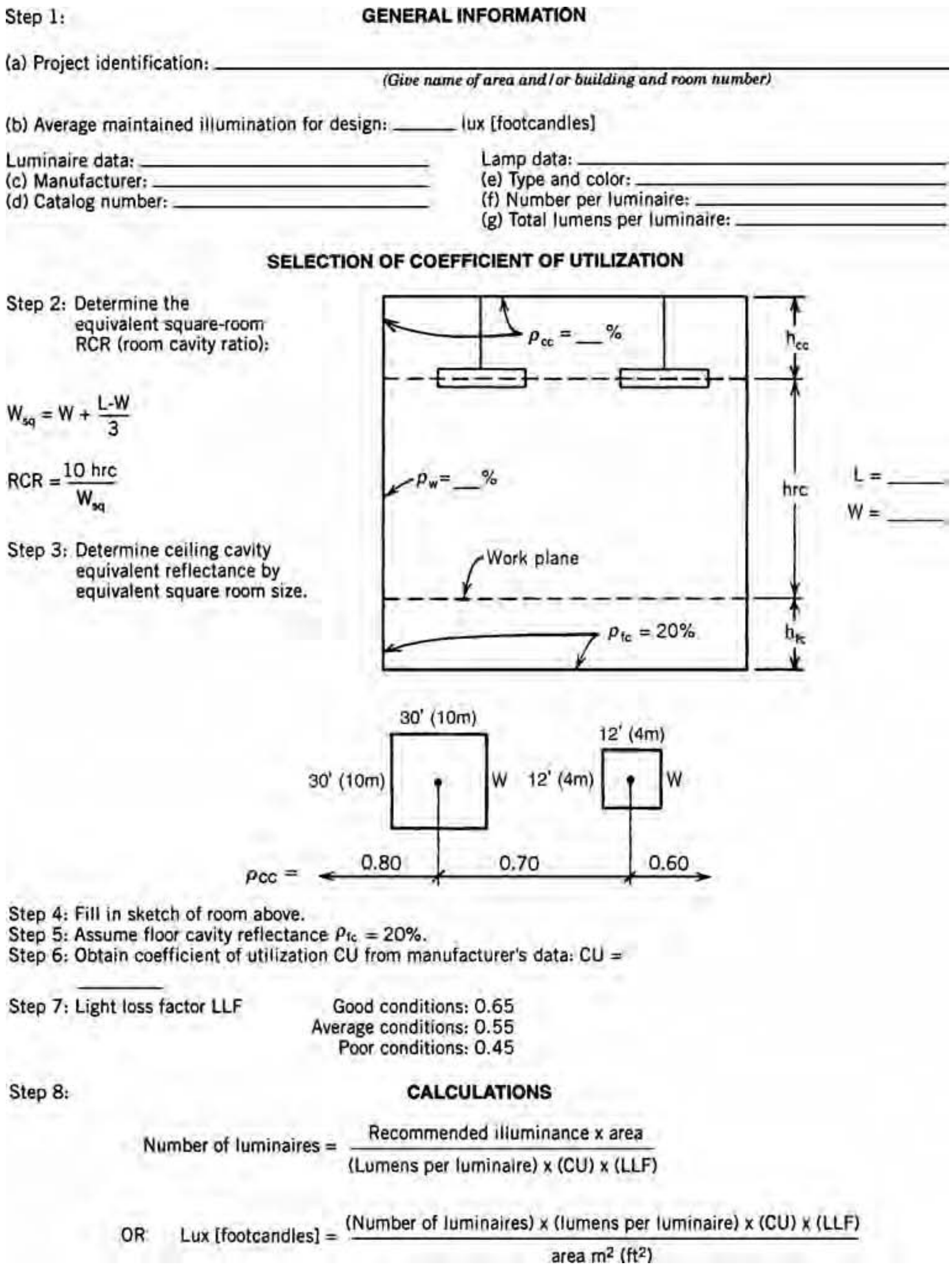
1. $w_{SQ} = 60 + \dfrac{100-60}{3} = 73\ \mathrm{ft}$
2. $\rho_{CC} = 80;\ \rho_{w} = 50;\ \rho_{FC} = 20$
3. $\mathrm{RCR} = \dfrac{10 \times 5.5}{73} = \dfrac{55}{73} = 0.75$
4. CU = 0.66 by inspection (mental interpolation)
5. LLF = 0.55
6. $\text{area / luminaire} = \dfrac{2 \times 2800 \times 0.66 \times 0.55}{50\ \mathrm{fc}}$

$$= 40.6\ \text{sq ft}\ (3.8\ \mathrm{m}^2)$$

This result is within 5.5% of the more precise calculation. Thus, we see that these simple approximations give answers sufficiently accurate for most uses and are therefore recommended. ■

In conclusion, then, with respect to zonal cavity calculations, we can make the following statements:

1. For preliminary and routine calculations of rectangular rooms, with assumed reflectances, use the assumptions listed previously.


Step 1: **GENERAL INFORMATION**

(a) Project identification: ______________________________
(Give name of area and/or building and room number)

(b) Average maintained illumination for design: ______ lux [footcandles]

Luminaire data: ______________________
(c) Manufacturer: ______________________
(d) Catalog number: ______________________

Lamp data: ______________________
(e) Type and color: ______________________
(f) Number per luminaire: ______________________
(g) Total lumens per luminaire: ______________________

SELECTION OF COEFFICIENT OF UTILIZATION

Step 2: Determine the equivalent square-room RCR (room cavity ratio):

$$W_{sq} = W + \frac{L-W}{3}$$

$$RCR = \frac{10\ hrc}{W_{sq}}$$

Step 3: Determine ceiling cavity equivalent reflectance by equivalent square room size.

Step 4: Fill in sketch of room above.
Step 5: Assume floor cavity reflectance ρ_{fc} = 20%.
Step 6: Obtain coefficient of utilization CU from manufacturer's data: CU = ________

Step 7: Light loss factor LLF

Good conditions: 0.65
Average conditions: 0.55
Poor conditions: 0.45

Step 8: **CALCULATIONS**

$$\text{Number of luminaires} = \frac{\text{Recommended illuminance x area}}{\text{(Lumens per luminaire) x (CU) x (LLF)}}$$

$$\text{OR} \quad \text{Lux [footcandles]} = \frac{\text{(Number of luminaires) x (lumens per luminaire) x (CU) x (LLF)}}{\text{area m}^2\text{ (ft}^2\text{)}}$$

Fig. 16.38 *Sheet for illuminance calculation using an approximate zonal cavity method (based on a method developed by B. F. Jones).*

A modified calculation form is provided in Fig. 16.38 to assist with this method.

2. For rooms where a high degree of accuracy is desired and actual reflectances are known, use the long method with visual interpolation.
3. For rooms of unusual shape or rooms with special conditions, such as coffered ceilings, mixed-material walls, and partial height partitions, use computer assistance.
4. For spaces in which a number of different solutions are to be tried, use a computer.

16.24 EFFECT OF CAVITY REFLECTANCES ON ILLUMINANCE

The reflectances of the various room cavities have a marked effect on the CU because of light reflections within the room. To demonstrate this graphically, we have plotted in Figs. 16.39, 16.40, and 16.41 the effect of varying cavity reflectances on three common types of fixture distribution: semi-indirect, direct–indirect, and direct-spread. Note that as expected, ceiling cavity reflectance has the most pronounced effect with indirect-component fixtures and floor reflectance with direct units. Because lighting costs amount to 3% to 5% of the total construction cost for many types of buildings such as offices, a 20% differential in lighting fixtures can amount to as much as 1% of the total cost of a facility. This amount would not only pay for the increased cost of higher-reflectance finishes and materials but would also reduce both initial and operating costs. These data clearly indicate the necessity for the lighting designer to have considerable influence on the selection of room materials and finishes, a situation that, unfortunately, does not usually occur.

16.25 MODULAR LIGHTING DESIGN

An increasingly large number of buildings are being designed around a modular system, resulting in a need for flexible lighting to fit the module utilized. In such buildings, once the general lighting scheme and luminaire are established, it is convenient to draw a family of curves for the fixture chosen, thereby facilitating the utilization of the modular unit in various spaces. "Area" may readily be replaced with multiples of modular areas, as shown in Fig. 16.42.

16.26 CALCULATING ILLUMINANCE AT A POINT

The lumen (flux) method of horizontal illuminance calculation explained previously is appropriate for spaces in which illuminance is essentially uniform throughout. However, even in such a space, illuminance varies at least ±10% and, near columns, walls, windows, bookcases, and the like, considerably more. Therefore, to answer the often asked question "How much light will I have on my desk?"

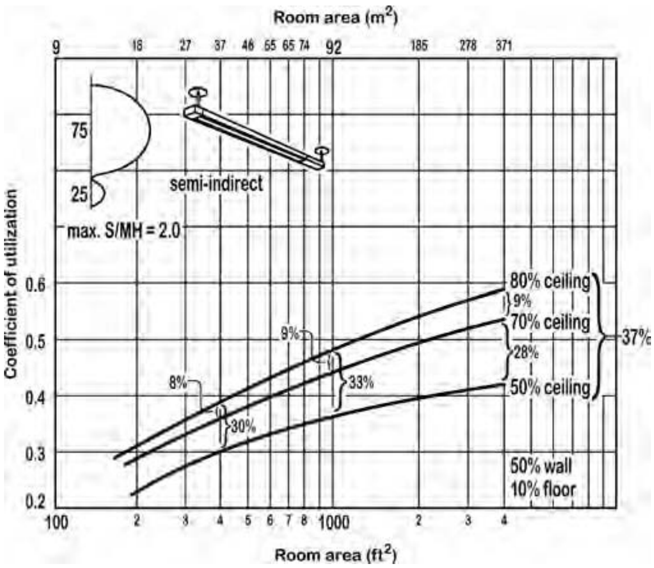
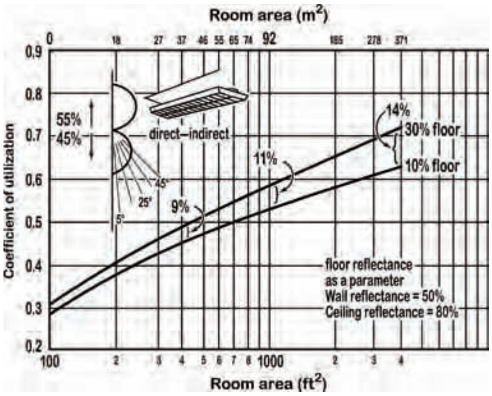
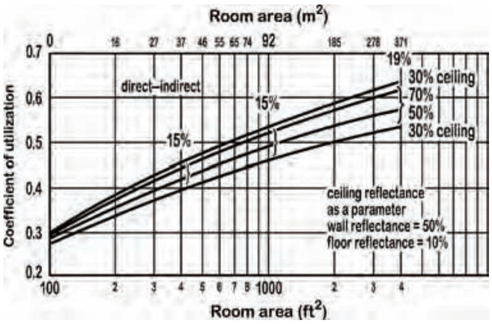


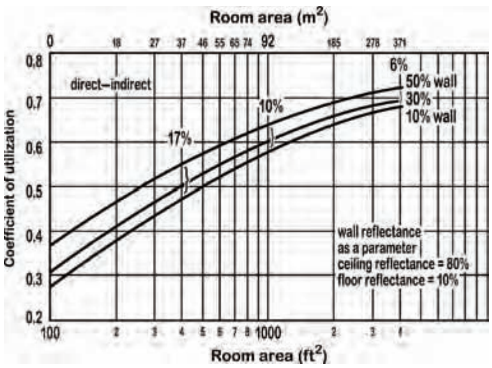
Fig. 16.39 *Effect of surface reflectances on the CU of a luminaire with semi-indirect distribution. As expected, because the ceiling becomes the light source, its reflectance has the most pronounced effect. With this particular unit having a 25% downward component, the floor finish also has an appreciable effect, increasing the CU by an average of 10% for a 30% reflectance floor. The effect of wall reflectance naturally increases as rooms become smaller and the proportion of wall surface becomes larger. The change in CU between a 30% and a 50% reflectance wall varies from 15% for a 400-ft² (37-m²) room to 5% for a 4000-ft² (372-m²) room. (Redrawn with SI units by Lisa Leal.)*



(*a*)



(*b*)



(*c*)

Fig. 16.40 *Effect of surface reflectances (a: floor, b: ceiling, c: wall) on the CU of a luminaire with direct–indirect distribution. With this distribution, the effects of the ceiling and floor are most pronounced, with an appreciable wall effect only in small rooms. (Redrawn with SI units by Lisa Leal.)*

the designer must turn to other methods. Two are available:

1. Utilization of one of the design aids explained in Section 16.27
2. Longhand calculation by one of the methods presented in Sections 16.28 through 16.30

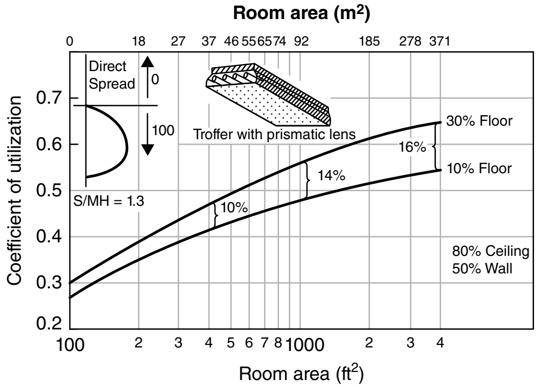


Fig. 16.41 *Effect of surface reflectances on the CU of a luminaire with direct (spread) distribution. Floor finish is most important, with wall reflectance important only in small rooms. As these fixtures have no upward component, all ceiling illumination is derived from reflection. Thus, in a room with floor reflectance of less than 20%, ceiling finish has no effect on room illumination.*

These methods also yield results where the lumen method is simply inapplicable. Among such situations are layouts that are intentionally nonuniform; calculation of illuminance on planes other than horizontal (e.g., wallwashers); calculation of illuminance resulting from architectural lighting elements such as coves, valances, and the like; and illuminance calculations for nonstandard light sources for which CU data of the type given in Table 16.1 are not available.

16.27 DESIGN AIDS

By *design aids* we mean any of the various curves, charts, plots, or tables—either prepared by the designer or made available by luminaire manufacturers—the purpose of which is to simplify and speed lighting design when using a particular lighting fixture. The reliability of data so obtained depends entirely on the manufacturer involved, and their use should be governed accordingly. More recently, it has become customary for major manufacturers to provide computer output charts and tables based on the designers' proposed layout(s). When using these, it behooves the designer to carefully study the data input to the computer program, as the fixture supplier is certainly not a disinterested party, and the program may be "weighted" accordingly. A brief description of common design aids follows.

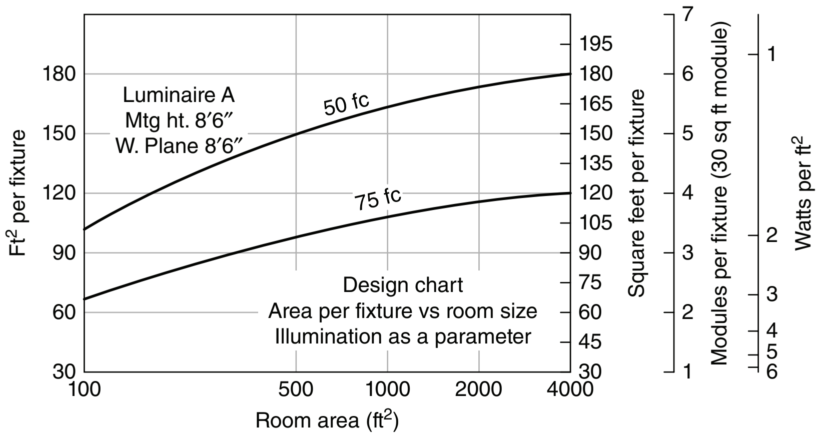
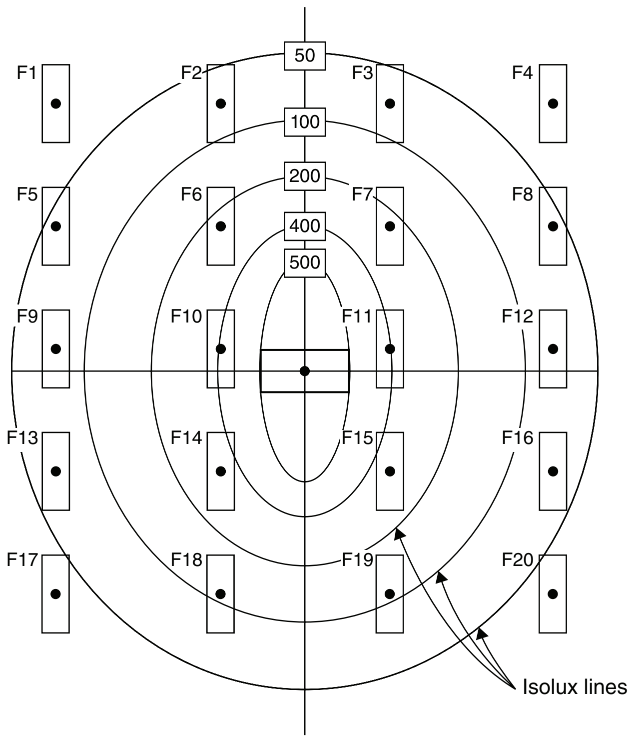


Fig. 16.42 *Luminaire design chart. For frequently used fixtures, this type of chart gives an easy design figure for various size rooms. As seen from the ordinates, the figures can be translated into number of modules and watts per square foot.*

(a) Isolux Charts

These charts, also called *isofootcandle charts*, are based on the type traditionally supplied by manufacturers of outdoor lighting equipment, such as street lights and floodlights, but are equally applicable to interior lighting. Their use is illustrated in Fig. 16.43. The basic tool is an isolux diagram for a single luminaire. This is either calculated (see Sections 16.28–16.29), measured from a full-scale



Luminaire	*Contribution (Lux)*
F2, F3	75 × 2
F5, F8	50 × 2
F6, F7	225 × 2
F9, F12	75 × 2
F10, F11	400 × 2
F13, F16	60 × 2
F14, F15	300 × 2
F18, F19	100 × 2
	2570 lux total

Fig. 16.43 *The ellipses represent isolux lines for a single luminaire at a given height above the work plane. They are centered on the point (the work area of a desk) for which the illuminance must be determined. The total illuminance at that point is the sum of the individual luminaire contributions. The center of the luminaire is the point of reference. Therefore, when two or more isolux lines pass through a fixture, its contribution is determined by the interpolated isolux line passing through its center. Note the symmetry around the vertical axis, necessitating a plot of only half of the ellipses.*

mock-up (the most accurate if not the most practical method), or obtained from the manufacturer. Inasmuch as the relative positions of the source and illuminated point are reversible—that is, if a source at *A* causes illuminance *E* at point *B*, then the source at *B* will cause the same illuminance *E* at point *A*—placing the center of the isolux chart at the point in question permits direct reading of the illuminance contribution of every other luminaire. It then remains simply to sum the individual contributions to obtain the (scalar) illuminance at the desired point. An example is shown in Fig. 16.43.

(b) Illuminance "Cone" Charts

See Fig. 16.44. When the light distribution of a direct downlight is symmetrical, as is generally the case, a cone can be drawn showing the illuminance directly under the fixture at various distances. The projected circles are defined by maximum illuminance at the center and half of this illuminance at the edge. This projected circle can be used in the same fashion as the isolux chart in the preceding section, except that only two values are given—that at the center and that on the circumference.

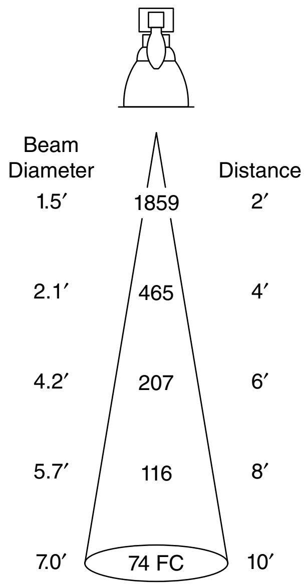
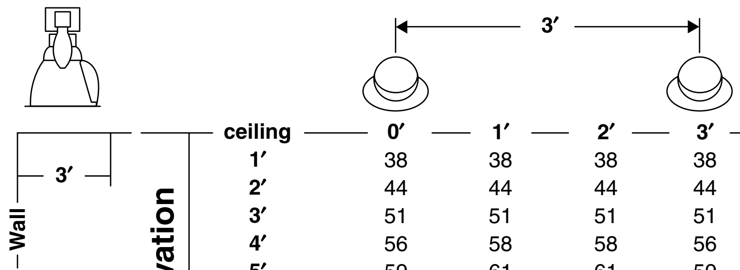


Fig. 16.44 *For downlights with symmetrical circular distribution, a "cone of light," as shown, can be drawn. The illuminance at varying distances on the beam centerline directly below the luminaire is given in the center column. A circle with a circumference at which the illuminance is half of this maximum is drawn at each distance from the downlight (2 ft, 4 ft, etc.). The numbers in the left column show the diameter of this (beam) circle. (Courtesy of Zumtobel-STAFF.)*

(c) Illuminance Tables and Charts

These take various forms but all give specific illuminance data, in numerical form, for specific points. The values are obtained from a computer printout or an actual test. Fig. 16.45 shows the illuminance pattern on a wall produced by the wallwasher version of the downlight shown in Fig. 16.44. The difference between the two fixtures is the addition of an interior reflector in the wallwasher version.

Wallwash Lighting Data Chart



Elevation	0′	1′	2′	3′
ceiling				
1′	38	38	38	38
2′	44	44	44	44
3′	51	51	51	51
4′	56	58	58	56
5′	59	61	61	59
6′	58	57	57	58
7′	52	49	49	52
8′	42	42	42	42
9′	18	18	18	18
floor	33	33	33	33

Fig. 16.45 *Addition of an interior reflector to the downlight of Fig. 16.44 converts it to a dual-purpose downlight and wallwash unit. The wall illuminances produced by multiple units spaced 3 ft (0.9 m) apart and ceiling-mounted 3 ft (0.9 m) from the wall are given in the chart. Similar charts are available for other luminaire spacings. (Courtesy of Zumtobel-STAFF.)*

16.28 CALCULATING ILLUMINANCE FROM A POINT SOURCE

It is well to note at the outset that all of the following methods calculate illuminance at a *point*. The answer to the query "How much light will I have on my desk from a luminaire at this location?" is arrived at by taking several points on the desk and calculating illuminance at each one. Shortcuts can be made for symmetry and so on. Most of these calculations are lengthy and are generally performed by a consulting engineer or lighting specialist rather than the architect. They are presented here as background material to describe the nature of lighting design.

The basis of point source calculations is the inverse square law developed in Section 13.12:

$$fc = \frac{cp}{D^2}$$

where *fc*, *cp*, and *D* are footcandle illuminance, candlepower intensity, and distance, respectively. Refer to Fig. 16.46. The horizontal illuminance at a point *P* as shown in Fig. 16.46 is

$$\text{horizontal } E = \frac{cp}{D^2} \cos\theta \qquad (16.14)$$

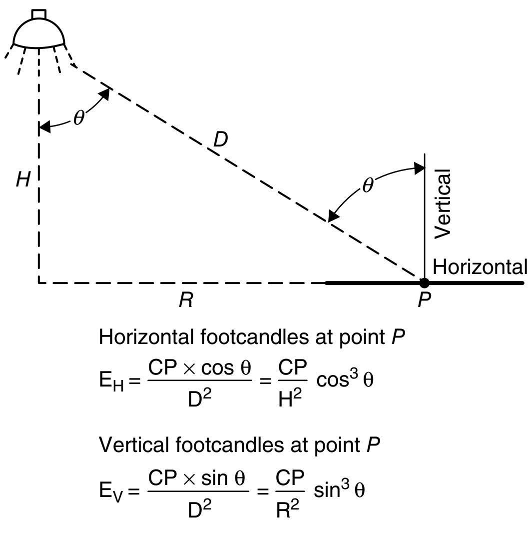


Fig. 16.46 *Relationship between intensity in candlepower (cp) and illuminance when the source can be considered a point source—that is, when the inverse square law applies. Source major dimension must not exceed 0.2D to be considered a point source. Measurement in feet yields fc; distances in meters yield lux.*

and the vertical illuminance at that same point is

$$\text{vertical } E = \frac{cp}{D^2} \sin\theta \qquad (16.15)$$

However, because

$$\cos\theta = \frac{H}{D} \text{ and } \sin\theta = \frac{R}{D}$$

we have then at point *P*

$$\text{Horizontal illuminance: } \frac{cp}{H^2} \times \cos^3\theta \qquad (16.16)$$

$$\text{Vertical illuminance: } \frac{cp}{R^2} \times \sin^3\theta \qquad (16.17)$$

Inasmuch as the candlepower intensity in the direction of point *P* is taken from a candlepower distribution curve, and θ is known, these expressions are readily usable. Very few commercial light sources are actually point sources. However, *when the maximum dimension of the source is less than five times the distance to point P*, the equations give satisfactory results. Note that these equations can be used to calculate and plot isolux diagrams for point sources of the type shown in Figs. 16.43 and 16.44.

EXAMPLE 16.5 Referring to Fig. 16.46 and the candlepower distribution curve of Fig. 16.47, find the horizontal and vertical illuminance at point *P*,

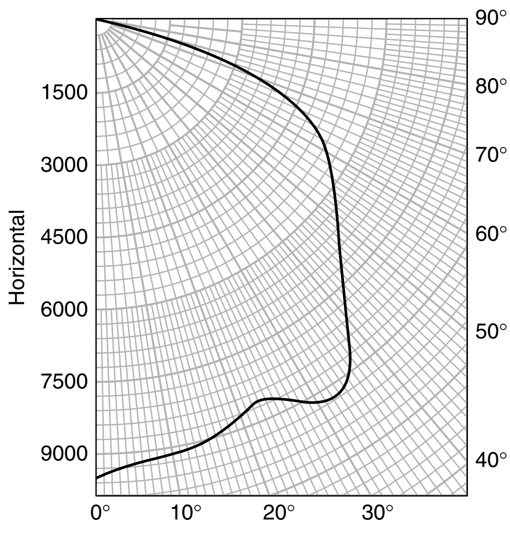


Fig. 16.47 *Typical candlepower distribution plot for use in inverse square law calculation.*

which is 10 ft (3 m) below and 12 ft (3.7 m) horizontally distant from the source.

SOLUTION

$$H = 10 \text{ ft} \quad R = 12 \text{ ft}$$

$$\theta = \tan^{-1}\frac{12}{10} = 50°$$

$$\sin\theta = 0.766 \qquad \cos\theta = 0.643$$

$$cp \text{ at } 50° = 6600 \text{ (from Fig. 16.47)}$$

$$\text{Horizontal illuminance: } \frac{6600}{10^2} \times (0.643)^3 = 17.5 \text{ fc}$$

$$\text{Vertical illuminance: } \frac{6600}{12^2} \times (0.766)^3 = 20.8 \text{ fc}$$

■

16.29 CALCULATING ILLUMINANCE FROM LINEAR AND AREA SOURCES

When the source is too large to be considered a point source (the definition is relative and depends on the distance to the illuminated surface), it is referred to as either a *linear source* or an *area source*. The *direct component* of the illuminance at a point, resulting from such sources, can be calculated by manual graphical or analytical means, both of which are based on an assumed distribution, generally Lambertian (diffuse). Inasmuch as most lighting fixtures being applied today do *not* have Lambertian characteristics (e.g., parabolic reflectors, prismatic diffusers), the results of such calculations are necessarily approximate. (Skylights and luminous ceilings *do* have a Lambertian distribution, and for these sources these calculation methods do give reliable results.) In addition to the direct component of illuminance, a *reflected component* must be added that depends on the point's location in the room and the room characteristics. The calculations involve charts, diagrams, and tables. The interested reader will find a full description of these manual methods in the *IESNA Lighting Handbook*.

Because these manual methods are laborious and frequently less than reliable, they are not presented here. The ready availability of personal computers and computer programs that can handle detailed input for a specific light source, without broad approximations, has made these manual procedures obsolete. We recommend that when point-by-point illuminance calculation is desired, such a program be used. Alternatively, one of the design aids described previously, based on a specific light source, can be used.

16.30 COMPUTER-AIDED LIGHTING DESIGN

As pointed out in previous sections, the use of computers in lighting design is a practical necessity if really useful results are to be obtained. Once the desired luminance patterns and illuminance levels have been established, and luminaires selected and located by using either average illuminance (zonal cavity) calculations or one of the design aids previously demonstrated and/or the manufacturer's assistance, the responsible designer will confirm the preliminary design solution with accurate calculations. Furthermore, only a computer analysis will give useful point-by-point illuminance figures plus valuable data on VCP and reflected glare for selected work locations and viewing directions.

In addition, computer analysis gives the designer a degree of flexibility not otherwise possible, in that:

1. The calculations are performed accurately and rapidly.
2. The designer is freed for other, less routine work.
3. The designer has the ability to change parameters repeatedly without making the analysis excessively burdensome, as would be the case with hand calculations.

It is this last characteristic that gives the designer greatest flexibility. The ability to run a series of calculations for a pendant fixture with varying pendant lengths, or to change paint colors and reflectances for various surfaces and note the effect, or to test different layout patterns, as mentioned in Example 16.2, gives the designer a very powerful and extremely useful design tool. In addition, computer analysis can consider related items, such as first costs, energy use, operating costs, and impact on HVAC systems—items whose complexity because of interrelations puts them well beyond the pencil-and-hand-calculator's ability. A few lighting analysis programs currently available are listed in Appendix L.

16.31 AVERAGE LUMINANCE CALCULATIONS

The basic equations relating luminance to candela intensity and to illuminance are covered in Section 13.8, which also deals with the calculation of source luminance and reflected luminance when the illuminance is known. Thus, once horizontal illuminance has been calculated by any of the methods described previously and the reflectance of an object is known, its horizontal luminance can readily be calculated (see Section 13.8). However, as explained in detail in Sections 13.32 and 13.33 (which discuss lighting quality) and in Sections 15.10 through 15.16 (which deal with lighting systems and patterns), the luminance impression of a visual environment is affected more by vertical than by horizontal surface luminance. For this reason, it is important to be able to calculate *average* vertical surface (wall) luminance in the same simple, straightforward fashion used to calculate *average* horizontal illuminance. In addition, it is useful to know the average luminance of the ceiling cavity in a space in order to judge the contrast between all luminous objects, including luminaires, that have the ceiling cavity as background.

Straightforward calculation of both wall and ceiling cavity luminance (L_W and L_{CC}) is possible through the use of luminance coefficients that are similar in concept and application to coefficients of utilization. These coefficients are listed in Table 16.4 for some of the generic fixture types listed in Table 16.1. Others are listed in the *IESNA Lighting Handbook*. For actual design calculations, it is preferable to obtain coefficients from luminaire manufacturers. The average luminance calculations are parallel to those for illuminance.

Average initial wall luminance (cd/m^2):

$$L_W = \frac{\text{lamp lumens} \times \text{ceiling cavity luminance coefficient}}{\pi \times \text{floor area in m}^2} \qquad (16.18)$$

and average initial ceiling cavity luminance in cd/m^2:

$$L_{CC} = \frac{\text{lamp lumens} \times \text{wall luminance coefficient}}{\pi \times \text{floor area in m}^2} \qquad (16.19)$$

If area is expressed in square feet and π is omitted from these equations, L will be expressed in footlamberts.

To obtain *maintained* values, an LLF similar to that explained in Section 16.20 is introduced. It is calculated similarly, except that item 17 (see Fig. 16.35), room surface dirt, is calculated using the following values:

Lighting System	Wall Luminance	Ceiling Luminance
Direct	0.82610%	0.75610%
Semi-direct	0.8767%	0.82610%
Direct–indirect	0.9265%	0.8568%
Semi-indirect	0.8767%	0.8867%
Indirect	0.82610%	0.9065%

For ceiling-mounted or recessed luminaires, L_{CC} is the average luminance of the ceiling between luminaires. For pendant luminaires, the calculated L_{CC} is that of an imaginary plane at the height of the luminaires. L_{CC} is useful in determining the brightness ratios when compared to luminaire luminance at the seeing angle involved. The ceiling cavity, like the wall, is assumed to have a Lambertian characteristic—that is, perfect diffuseness—making luminance independent of viewing angle.

It would be instructive to calculate the wall luminance of the office in Example 16.2. The photometric data in Fig. 16.37 do not include the wall luminance coefficient because luminance coefficients are not normally published by luminaire manufacturers. However, based on other available data, a figure of 0.22 for wall luminance is a good estimate given RCR, ρ_{CC}, and ρ_W of 0.66, 80%, and 30%, respectively. Initial wall luminance is then

$$L_W = \frac{3200 \times 0.22}{32 \text{ ft}^2} = 22 \text{ fL} = 75.5 \text{ cd/m}^2$$

This is within the preferred range of 25 to 150 cd/m^2 (see Table 13.3). In actuality, the average wall luminance would probably be higher because of the practice of placing the last row of luminaires quite close to the wall.

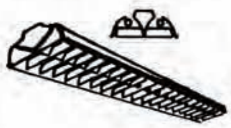
EVALUATION

16.32 LIGHTING DESIGN EVALUATION

The final step in lighting design is evaluation of the design relative to three key aspects—lighting, cost, and energy. The lighting aspects include quantity,

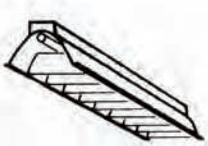
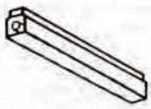
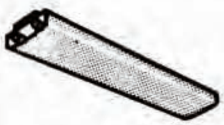
TABLE 16.4 Wall Luminance Coefficients and Ceiling Cavity Luminance Coefficients for Typical Luminaires

To obtain a luminance coefficient, follow the procedure detailed at the beginning of Table 16.1 for finding a CU. More precise design data should be obtained from the manufacturers of the actual luminaires used.

	ρ_{CC}:	80			50			80		50	
	ρ_W:	50	30	10	50	30	10	50	30	50	30
Typical Luminaire	*RCR*	*Wall Luminance Coefficients for ρ_{FC} = 20*						*Ceiling Cavity Luminance Coefficient ρ_{FC} = 20*			
1 	0							.42	.42	.25	.25
	1	.32	.18	.06	.27	.15	.05	.42	.40	.25	.23
	2	.27	.15	.05	.23	.13	.04	.42	.38	.24	.23
	3	.24	.13	.04	.20	.11	.03	.41	.37	.24	.22
	4	.21	.11	.03	.17	.09	.03	.41	.36	.24	.22
	5	.19	.10	.03	.16	.08	.02	.40	.35	.24	.21
	6	.18	.09	.03	.14	.07	.02	.39	.34	.23	.21
	7	.16	.08	.02	.13	.07	.02	.39	.34	.23	.21
	8	.15	.07	.02	.12	.06	.02	.38	.34	.23	.20
Pendant diffusing sphere	9	.14	.07	.02	.12	.06	.02	.38	.33	.23	.20
with incandescent lamp	10	.13	.06	.02	.11	.05	.01	.37	.33	.22	.20
3 	0							.15	.15	.09	.09
	1	.23	.13	.04	.21	.12	.04	.15	.13	.09	.08
	2	.22	.12	.04	.21	.11	.04	.14	.11	.08	.07
	3	.21	.11	.03	.20	.11	.03	.13	.10	.08	.06
	4	.20	.10	.03	.19	.10	.03	.13	.08	.08	.05
	5	.19	.09	.03	.18	.09	.03	.12	.08	.07	.05
	6	.18	.09	.03	.17	.09	.02	.12	.07	.07	.04
	7	.17	.08	.02	.16	.08	.02	.11	.06	.07	.04
Porcelain-enameled	8	.16	.08	.02	.15	.07	.02	.11	.06	.06	.04
ventilated standard dome	9	.15	.07	.02	.14	.07	.02	.10	.05	.06	.03
with incandescent lamp	10	.14	.07	.02	.13	.07	.02	.10	.05	.06	.03
7 	0							.08	.08	.04	.04
	1	.06	.03	.01	.05	.03	.01	.08	.07	.04	.04
	2	.05	.03	.01	.05	.03	.01	.07	.06	.04	.04
	3	.05	.03	.01	.04	.02	.01	.06	.05	.04	.03
	4	.05	.02	.01	.04	.02	.01	.05	.04	.03	.03
	5	.05	.02	.01	.04	.02	.01	.05	.04	.03	.02
	6	.04	.02	.01	.04	.02	.01	.05	.03	.03	.02
Reflector downlight with	7	.04	.02	.01	.04	.02	.01	.04	.03	.03	.02
baffles and inside-frosted	8	.04	.02	.01	.04	.02	.01	.04	.03	.02	.02
lamp (see note on this unit	9	.04	.02	.01	.04	.02	.01	.04	.02	.02	.02
in Table 15.1)	10	.04	.02	.00	.04	.02	.01	.04	.02	.02	.01
28 	0							.27	.27	.16	.16
	1	.17	.10	.03	.14	.08	.03	.26	.24	.15	.14
	2	.16	.09	.03	.14	.08	.02	.25	.23	.15	.14
	3	.15	.08	.02	.13	.07	.02	.24	.21	.14	.13
	4	.15	.08	.02	.13	.07	.02	.24	.21	.14	.12
	5	.14	.07	.02	.12	.06	.02	.23	.20	.14	.12
	6	.13	.07	.02	.11	.06	.02	.23	.19	.14	.12
	7	.13	.06	.02	.11	.06	.02	.23	.19	.13	.11
Diffuse aluminum reflector	8	.12	.06	.02	.11	.05	.02	.22	.18	.13	.11
with 35° crosswise and 35°	9	.12	.06	.02	.10	.05	.01	.22	.18	.13	.11
lengthwise shielding	10	.11	.05	.01	.10	.05	.01	.22	.18	.13	.11
33 	0							.65	.65	.38	.38
	1	.20	.12	.04	.13	.08	.02	.65	.63	.38	.37
	2	.19	.10	.03	.12	.07	.02	.64	.61	.38	.37
	3	.17	.09	.03	.11	.06	.02	.64	.60	.37	.36
	4	.16	.08	.02	.11	.06	.02	.63	.59	.37	.36
	5	.15	.08	.02	.10	.05	.02	.63	.59	.37	.36
	6	.14	.07	.02	.09	.05	.01	.60	.58	.37	.35
	7	.13	.07	.02	.09	.04	.01	.62	.58	.37	.35
Luminous bottom-	8	.12	.06	.02	.08	.04	.01	.61	.57	.37	.35
suspended unit with extra-	9	.12	.06	.02	.08	.04	.01	.61	.57	.36	.35
high-output lamp	10	.11	.05	.01	.07	.04	.01	.61	.57	.36	.35

(continued)

TABLE 16.4 Wall Luminance Coefficients and Ceiling Cavity Luminance Coefficients for Typical Luminaires (*Continued*)

	ρ_{CC}:	80			50			80		50	
	ρ_W:	50	30	10	50	30	10	50	30	50	30
Typical Luminaire	*RCR*	*Wall Luminance Coefficients for ρ_{FC} = 20*						*Ceiling Cavity Luminance Coefficient ρ_{FC} = 20*			
44	0							.114	.114	.066	.066
	1	.137	.078	.025	.125	.072	.023	.105	.094	.061	.055
	2	.131	.072	.022	.121	.067	.021	.097	.079	.057	.047
	3	.127	.068	.020	.118	.064	.019	.092	.068	.054	.041
	4	.123	.064	.019	.115	.061	.018	.087	.060	.052	.036
	5	.119	.060	.018	.112	.058	.017	.084	.053	.050	.032
	6	.114	.057	.016	.108	.055	.016	.080	.048	.048	.029
	7	.110	.054	.015	.104	.053	.015	.078	.044	.046	.027
Radial batwing	8	.106	.052	.015	.101	.050	.014	.075	.041	.045	.025
distribution—louvered	9	.102	.049	.014	.097	.048	.014	.073	.038	.043	.023
fluorescent, unit	10	.097	.047	.013	.093	.046	.013	.070	.036	.042	.022
46	0							.236	.236	.138	.138
	1	.234	.133	.042	.208	.119	.038	.229	.210	.134	.124
	2	.213	.117	.036	.190	.106	.033	.222	.193	.130	.115
	3	.195	.104	.031	.175	.095	.029	.216	.180	.127	.108
	4	.181	.094	.028	.162	.086	.026	.211	.170	.124	.102
	5	.170	.087	.025	.153	.080	.023	.206	.163	.122	.098
Bilateral batwing	6	.159	.080	.023	.143	.073	.021	.201	.157	.119	.095
distribution—one lamp,	7	.149	.074	.021	.135	.068	.020	.197	.152	.117	.092
surface-mounted	8	.141	.069	.019	.128	.064	.018	.193	.148	.115	.090
fluorescent, with prismatic	9	.134	.065	.018	.121	.060	.017	.189	.144	.113	.088
wraparound lens	10	.126	.061	.017	.115	.056	.016	.185	.141	.111	.086
35	0							.22	.22	.13	.13
	1	.19	.11	.03	.17	.10	.03	.21	.20	.12	.12
	2	.18	.10	.03	.15	.09	.03	.21	.18	.12	.11
	3	.16	.09	.03	.14	.08	.02	.20	.17	.12	.10
	4	.15	.08	.02	.14	.07	.02	.19	.16	.11	.10
	5	.14	.07	.02	.13	.07	.02	.19	.15	.11	.09
	6	.14	.07	.02	.12	.06	.02	.18	.15	.11	.09
	7	.13	.06	.02	.12	.06	.02	.18	.14	.11.	.09
Two-lamp prismatic	8	.12	.06	.02	.11	.05	.02	.18	.14	.11	.08
wraparound—multiply by	9	.12	.06	.02	.11	.05	.01	.17	.13	.10	.08
0.95 for four lamps	10	.11	.05	.01	.10	.05	.01	.17	.13	.10	.08
42	0							.12	.12	.07	.07
	1	.16	.09	.03	.15	.09	.03	.11	.10	.06	.06
	2	.15	.08	.03	.14	.08	.02	.10	.08	.06	.05
	3	.15	.08	.02	.14	.07	.02	.10	.07	.06	.04
	4	.14	.07	.02	.13	.07	.02	.09	.06	.05	.04
	5	.13	.07	.02	.12	.06	.02	.09	.06	.05	.03
Fluorescent unit with flat	6	.12	.06	.02	.12	.06	.02	.09	.05	.05	.03
prismatic lens; four-lamp,	7	.12	.06	.02	.11	.06	.02	.08	.05	.05	.03
610-mm (2-ft)-wide—multiply by	8	.11	.05	.02	.11	.05	.02	.08	.04	.05	.03
1.05 for three lamps and 1.10	9	.11	.05	.01	.10	.05	.01	.08	.04	.05	.02
for two lamps	10	.10	.05	.01	.10	.05	.01	.07	.04	.04	.02
47	0							.114	.114	.066	.066
	1	.175	.100	.032	.163	.094	.030	.107	.093	.063	.055
	2	.168	.092	.028	.157	.087	.027	.102	.079	.060	.047
	3	.157	.083	.025	.147	.080	.024	.097	.068	.057	.041
	4	.147	.076	.022	.138	.073	.022	.093	.060	.055	.036
	5	.139	.071	.021	.131	.068	.020	.090	.054	.053	.033
Radial batwing	6	.130	.065	.019	.123	.063	.018	.086	.049	.051	.030
distribution—four-lamp,	7	.122	.060	.017	.116	.059	.017	.082	.045	.049	.027
610 mm (2-ft)-wide	8	.115	.056	.016	.110	.055	.016	.079	.042	.047	.025
fluorescent unit with flat	9	.109	.053	.015	.104	.052	.015	.076	.039	.045	.024
prismatic lens—see note 2	10	.103	.049	.014	.099	.048	.014	.072	.037	.043	.022

Source: Data extracted, with permission, from the *IESNA Lighting Handbook, Reference Volume* (1993). Coefficients for fixtures 1, 3, 7, 28, 33, 35, and 42 have been rounded to two decimal places.

Notes:

1. Refer to the manufacturer's catalog data for more precise values when a specific luminaire is proposed for use.
2. Multiply coefficients by 1.05 for three lamps and by 1.1 for two lamps.

quality, luminance ratios, mood, ambience, texture, color, variation, psychological impressions, orientation, and daylight use—in short, a review of all the lighting factors previously discussed in detail. A good deal of experience is required to visualize actual lighting results from design drawings. The novice designer would do well to have someone with such experience assist in doing the review. The other two aspects of evaluation—cost and energy—can be evaluated readily with the aid of the contractor's estimating figures for cost and a computer simulation for energy. These estimates ought to be compared to the cost and energy budget figures developed at the preliminary design stage.

As we have repeatedly stressed, the important cost figures are life-cycle cost, annual operating cost, and first cost for economic comparisons, operating budgets, and construction budgets, respectively. In Chapter 17 we present lighting recommendations for specific occupancies, accompanied by actual cost studies and energy analyses. Detailed cost studies—including the impact of lighting on air conditioning, the proportional cost of the wiring system, and the proper apportionment of costs—involve the entire building and can be accurately performed only by computer. Studies of this type are generally made by consulting engineers rather than architects, and then only after initial, operating, and total costs have been set in proper perspective for a particular job by the architect and client. This is necessary because often, as in the case with speculative construction, the client's overriding consideration is first cost, thereby rendering a complete cost analysis unnecessary. Any attempt to completely separate costs for lighting, HVAC, structure, and so on is arbitrary because of the intimate interactions among these elements. Lighting designers are well advised to keep themselves and the construction team aware of this if they are to fulfill their responsibility.

References and Resources

ASHRAE. 2013. ANSI/ASHRAE/IESNA Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

IESNA. 1981. *IES Lighting Handbook*, 7th ed. Illuminating Engineering Society of North America. New York, NY.

IESNA. 1993. *IESNA Lighting Handbook*, 8th ed. Illuminating Engineering Society of North America. New York, NY.

IESNA. 2000. *IESNA Lighting Handbook*, 9th ed. Illuminating Engineering Society of North America. New York, NY.

IESNA. 2011. *IESNA Lighting Handbook*, 10th ed. Illuminating Engineering Society of North America. New York, NY.

NEMA. 1998. NEMA LE5B-1998, *Procedure for Determining Luminaire Efficacy Ratings for High-Intensity Discharge Industrial Luminaires.* National Electrical Manufacturers Association. Rosslyn, VA.

NEMA. 1999. NEMA LE5A-1999, *Procedure for Determining Luminaire Efficacy Ratings for Commercial, Non-Residential Downlight Luminaires*. National Electrical Manufacturers Association. Rosslyn, VA.

NEMA. 2001. NEMA LE5-2001, *Procedure for Determining Luminaire Efficacy Ratings for Fluorescent Luminaires*. National Electrical Manufacturers Association. Rosslyn, VA.

NFPA. 2014. NFPA 70-2014: *National Electrical Code*. National Fire Protection Association. Quincy, MA.

UL. 2004. UL 1598, *Standard for Luminaires*. Underwriters Laboratories, Inc. Northbrook, IL.

CHAPTER 17

Electric Lighting Applications

17.1 INTRODUCTION

CHAPTERS 13 THROUGH 16 EXAMINED lighting fundamentals, sources, and design procedures. This chapter on lighting considers the application of lighting principles to specific situations—with a primary focus upon electric lighting systems. The facilities covered in some detail include residential, educational, commercial, institutional, and industrial occupancies. Each is examined from the viewpoint of its special requirements, and design approaches are suggested. The latter include lighting materials and sources as well as comparative economics and energy considerations. The chapter concludes with a consideration of special types of indoor lighting, plus a short section on exterior lighting.

RESIDENTIAL OCCUPANCIES

17.2 RESIDENTIAL LIGHTING: GENERAL INFORMATION

The buzzwords in modern residential construction are *automation* (convenience), *environmental considerations* (energy conservation, "green" design), and the *home as a working area* (home office, special communications considerations). These underlying considerations influence decisions on sources, control, energy use, and budget, as will be discussed later.

Residential lighting offers to the lighting designer a great opportunity for originality and ingenuity because a residence combines more diverse functions and needs than almost any other building. Furthermore, it often requires that all work be done at minimal cost and that the result please persons with a range of tastes. The designer approaches the problems with a list of requirements, a perception of the space, and two basic tools: the lighting fixture and the architectural lighting element. The former was discussed at length in Chapter 16.

There are numerous books and countless periodical articles devoted to residential lighting design. We recommend using Chapter 33 (Lighting for Residences) of the IES *Lighting Handbook* (10th ed.) as a reference and useful guide.

17.3 RESIDENTIAL LIGHTING: ENERGY ISSUES

Although residences are generally excluded from the requirements of ANSI/ASHRAE/IESNA Standard 90.1, and lighting is not seriously addressed by ANSI/ASHRAE Standard 90.2, there may be local code requirements that deal with lighting energy efficiency. In any case, there are energy implications associated with residential lighting design decisions. General energy efficiency recommendations include:

1. Provide means for multiple light levels in all areas. A kitchen during food preparation does not have the same lighting requirements as a kitchen being entered for a "refrigerator raid." Low-level lighting provisions should be made in *all* rooms, including bathrooms. To accomplish this, use high–low switches, simple dimmers, multilevel ballasts, and multilevel switching. An ancillary benefit is that ambience can be changed thereby in multiuse rooms such as dining rooms, family and recreation rooms, and finished basements.
2. Provide local task lighting for areas where relatively difficult visual tasks are performed, such as the kitchen location where menus are planned and accounts are handled.
3. Provide dimming and switching for accent lighting.
4. Use programmable timers with photocell override for exterior lighting.
5. In large residences, consider low voltage or wireless control for ease of remote control and energy savings (see Section 17.7).
6. Use daylight in areas normally occupied during daylight hours, such as kitchens and living rooms. Consider skylights with built-in electric lighting for these areas.

Although automatic daylight compensation is generally not justified economically, area switching is and should be considered in all spaces, including work areas of children's rooms and home offices.

17.4 RESIDENTIAL LIGHTING SOURCES

Incandescent sources have traditionally found very wide use in residences (despite their inefficiency) because of their desirable characteristics, which include flattering skin color, low first cost, small size, focusability, and simple, economical dimmability. Other sources with at least some of these characteristics and much higher efficiency should be considered:

- Fluorescent sources with color temperatures between 3000 and 3500 K can be used in kitchens and other work areas. Where linear fluorescent lamps are not desirable, compact fluorescent lamps (CFL) can readily be used. Keep in mind, however, that the lamp life of *all* fluorescent sources is shortened by switching.
- Architectural elements such as coves and cornices can readily use CFL lamps.
- Tungsten-halogen lamps should be restricted to highlighting and specialty requirements. They are incandescent lamps and, in addition to having low efficacy, must be carefully applied because of their concentrated heat.
- Consider employing low-wattage (9–12 W) compact fluorescent lamps in frequently used corridors and stairwells, rather than incandescents. These small lamps can be left on for extended periods to provide the required low-level lighting without the constant switching and lamp replacement required for incandescents. This practice is even more practical in difficult access areas such as stairwells.
- For closets, pantries, and other small areas with frequently switched lighting, incandescent lamps remain the source of choice.
- For home offices and dual-purpose areas that serve for both work and recreation, design the lighting for each use individually, with maximum common use. Fluorescent sources are recommended for work purposes.
- Bathrooms can use 3000 to 3500 K fluorescent sources for general lighting, a separate incandescent source for short-time use, and low-brightness globe-shaped incandescents for mirror lighting.
- Although many manufacturers produce downlights and wallwashers for CFL sources, none that we have seen delivers the "punch" of incandescents. Where such brightness is not required, CFL downlights are a good choice when burned for at least 3 hours per use.
- High-intensity discharge (HID) sources are appropriate for all exterior lighting.

17.5 RESIDENTIAL LIGHTING: DESIGN SUGGESTIONS

The following are a few general design suggestions:

- Use a general/task lighting approach, with the levels recommended in Tables 17.1 and 17.2.

TABLE 17.1 Illuminance Recommendations for General Lighting

Activity or Area	Average Lux
Conversation and relaxation	50–100[a]
Passage areas	50–100[a]
Areas other than kitchen	200–500
Kitchen	500–1000

[a]General lighting in these areas need not be uniform.

- Provide luminance ratios as in Fig. 17.1.
- Provide general lighting sufficient for movement and casual seeing in all spaces. Hallways require little lighting; stairs require more. Illuminate stairs from directly above or ahead to create a shadow directly below the tread front. Lighting from the front eliminates shadows and can create a safety hazard.
- Do *not* avoid ceiling light sources, as is so frequently done. Wide-profile ceiling fixtures provide general lighting; switch-controlled table lamps do not.
- Lighting in areas specifically intended for use by older occupants, such as "grandma apartments" that are part of larger residences and residential buildings intended for older occupants, should take cognizance of the special requirements listed in Section 13.23.

17.6 RESIDENTIAL LIGHTING: LUMINAIRES AND ARCHITECTURAL LIGHTING ELEMENTS

Guidelines that can assist the designer in selecting luminaires from the huge variety available commercially are as follows:

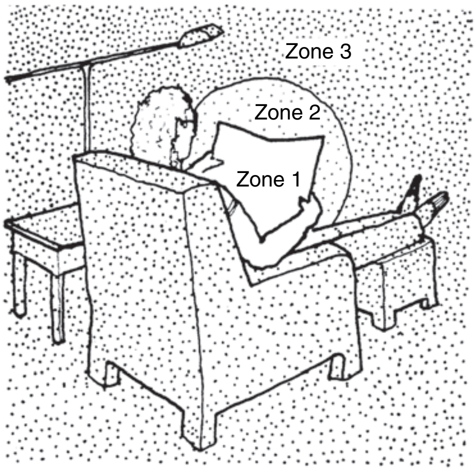
1. Utilize diffuse distribution for general lighting; narrow-distribution downlights for area and furniture accents; and narrow-distribution, ceiling-recessed incandescent wallwashers for accenting textured surfaces such as brick.

TABLE 17.2 Illuminance Recommendations for Specific Residential Visual Tasks[a]

Seeing Task	Typical North American Recommendation: Average Lux[b]	Other Authorities: Average Lux[b]
Dining	100–200	100–150
Grooming, makeup	200–500	500
HANDCRAFT		
Ordinary seeing tasks	200–500	200–500
Difficult seeing tasks	500–1000	500–750
Critical seeing tasks	1000–2000	>1250
KITCHEN DUTIES		
Food preparation and cleaning involving difficult seeing tasks	500–1000	750–1000
Serving and other noncritical tasks	200–500	200–300
Laundry tasks	200–500	100–300
Reading and writing		
Handwriting, reproductions, and poor copies	500–1000	750
Books, magazines, and newspapers	200–500	300
SEWING, HAND OR MACHINE		
Dark fabrics	1000–2000	>1250
Medium fabrics	500–1000	700–1000
Light fabrics	200–500	300–500
Table games	200–300	300

[a]Selection of illuminance within the given range is based on the criteria given in Section 13.24.

[b]Divide by 10 to get footcandles. Due to the range of values, use of the exact 10.76 conversion value is unnecessary.



Zone 2 The immediate surroundings (area adjacent to the visual task)	
Desirable ratio	1/3 to equal to task*
Minimum acceptable ratio	1/5 to equal to task*
Zone 3 The general surroundings (not immediataly adjacent to task)	
Desirable ratio	1/5 to 5 times task*
Minimum acceptable ratio	1/10 to 10 times task*

*Typical task luminance range is 40 to 120 cd/m^2 (12-35 fL) and seldom exceeds 200 cd/m^2 (60 fL)

Fig. 17.1 *Seeing zones and recommended luminance ratios for residential visual tasks.*

2. Use built-in lighting to the extent possible, including architectural lighting elements. We believe that this demonstrates integrity of concept. For this reason, we recommend that the flexibility of track lighting be utilized for accent and task lighting but not for general lighting (Fig. 17.2).
3. Private residences are the exception to the rule of selecting off-the-shelf items in preference to specials. The lighting should complement the architecture and furnishings, and frequently this can best be accomplished by original designs.

Architectural lighting elements include coves, cornices, valances, coffers, skylights, and other luminous constructions not normally constituting a lighting fixture. Although such units are normally less efficient than lighting fixtures, their use is often indicated by architectural considerations. Empirical design data are given in Figs. 17.3 and 17.4.

When using fluorescent lamps in architectural lighting elements, dark spots between lamps can be avoided by placing lamps at a slight angle rather than end to end, thus enabling ends to overlap. Similar overlapping is readily accomplished with PL lamps as well. Reflectors increase efficiency of an installation. When used in coves, reflectors should be aimed 15° to 25° above the horizontal and field-adjusted for the best ceiling coverage. When two-lamp strips are used, they should be arranged vertically, as shown in Fig. 17.4. Light output for a double-lamp installation rarely exceeds 1.75 times the single-lamp output.

17.7 RESIDENTIAL LIGHTING: CONTROL

In large residences, remote control of lighting becomes more of a necessity than a convenience from the viewpoints of control, safety, and status awareness. Completely wireless, radio-wave controlled lighting is particularly applicable to retrofit work because it requires only that control modules be substituted for existing switches. A conventional system might use a wall-mounted master at each entrance in the kitchen and in the home office

Fig. 17.2 *Track lighting is available with a wide variety of luminaire bodies. Those illustrated include a modular system to provide a practical approach to providing illumination in targeted areas. These feature 358-degree rotation and 90-degree tilt for precise aiming of halogen light sources to the object. In addition, a variety of single-circuit and multicircuit track designs are available. (Courtesy of Progress Lighting.)*

(*a*) Lighted Cornices

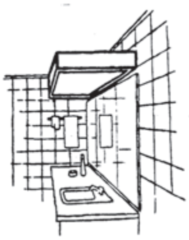
Cornices direct all their light downward to give dramatic interest to wall coverings, draperies, murals, etc. May also be used over windows where space above window does not permit valance lighting. Good for low-ceilinged rooms.

(*b*) Lighted Valances

Valances are always used at windows, usually with draperies. They provide up-light which reflects off ceiling for general room lighting and down-light for drapery accent. When closer to ceiling than 10 inches use closed top to eliminate annoying ceiling brightness.

(*c*) Lighted Coves

Coves direct all light to the ceiling. Should be used only with white or near-white ceilings. Cove lighting is soft and uniform but lacks punch or emphasis. Best used to supplement other lighting. Suitable for high-ceilinged rooms and for places where ceiling heights abruptly change.

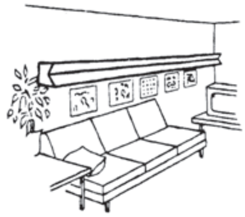


(*d*) Lighted Canopies

The canopy overhang is most applicable to bath or dressing room. It provides excellent general room illumination as well as light to the user's face.

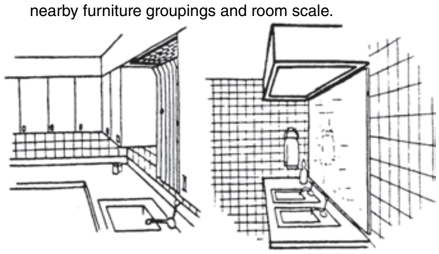
(*e*) Lighted High Wall Brackets

High wall brackets provide both up and down light for general room lighting. Used on interior walls to balance window valance both architecturally and in lighting distribution. Mounting height determined by window or door height.



(*f*) Lighted Low Wall Brackets

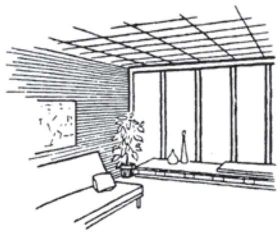
Low brackets are used for special wall emphasis or for lighting specific tasks such as sink, range, reading in bed, etc. Mounting height is determined by eye height of users, from both seated and standing positions. Length should relate to nearby furniture groupings and room scale.



(*g*) Lighted Soffits

Soffits over work areas are designed to provide higher levels of light directly below. Usually they are easily installed in furred-down area over sink in kitchen. Also are excellent for niches over sofas, pianos, built-in desks, etc.

Bath or dressing room soffits are designed to light user's face. They are almost always used with large mirrors and counter-top lavatories. Length usually tied to size of mirror. Add luxury touch with attractively decorated bottom diffuser.



(*h*) Luminous Wall Panels

Luminous wall panels create pleasant vistas; are comfortable background for seeing tasks; add luxury touch in dining areas, family rooms, and as room dividers. Wide variety of decorative materials available for diffusing covers.

Fig. 17.3 *Residential lighting elements. (Courtesy of IESNA.)*

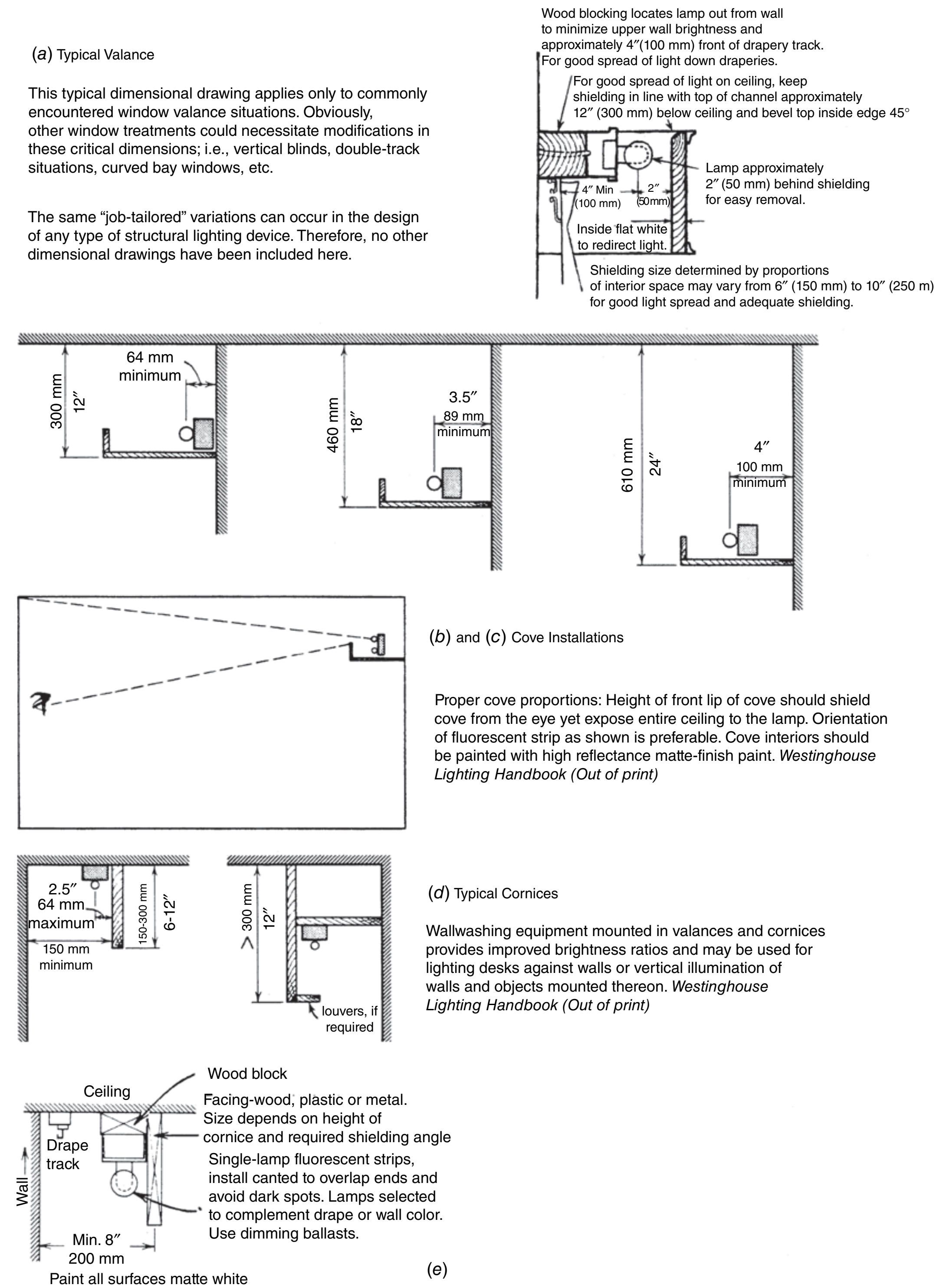


Fig. 17.4 *Selected lighting elements: construction details.*

Fig. 17.5 *Typical wall-mounted master station has five control buttons in addition to "All On" and "All Off" on every master. The control buttons can be arranged to control a single outlet or a group to establish lighting of a scene. Thus, the entry unit might have homecoming, extended absence, pathlighting, nightlighting, and garage-lighting scenes, whereas the kitchen master may have lighting scenes for breakfast, dinner, formal and informal entertaining, and night. Each scene can be arranged to turn on, brighten or dim, and shut off selected lighting. (Courtesy of Lutron Electronics Co., Inc.)*

Fig. 17.6 *Typical components of a wireless control system. Left to right:*

- *Bedside master station has five scene buttons and 10 individual outlet controls in addition to "All On" and "All Off" buttons.*
- *Repeater, which is used in large buildings to strengthen signals.*
- *Typical radio-controlled wall dimmer with local manual control. (Courtesy of Lutron Electronics Co., Inc.)*

(Fig. 17.5), a bedside tabletop master in the master bedroom (Fig. 17.6), and radio-operated wall switches and dimmers in all rooms.

EDUCATIONAL FACILITIES

17.8 INSTITUTIONAL AND EDUCATIONAL BUILDINGS

The lighting requirements for some spaces in educational facilities coincide with the requirements for commercial (office) and institutional buildings. To that extent, the remarks herein are applicable there as well. Generally, educational buildings (excluding private colleges and universities) are maintained by operating funds obtained from taxes, and the budget is *always* tight. Therefore, all equipment in these public buildings must be extremely hardy, vandal-proof, as maintenance-free as possible, and low in energy consumption. Maintenance in such buildings is generally poor and is performed on a repair rather than preventive basis. With these factors in mind, the following remarks apply to lighting equipment:

1. Use sources with the highest possible efficacy. Remember that daylight has the highest efficacy, followed by HPS, fluorescent, and metal–halide sources.
2. Where specific color lamps are called for, such as 3500 K T8 and the like, this requirement should be permanently stenciled in large letters on the lighting fixture to ensure proper relamping.
3. Long-life sources should always be given preference because of their lower maintenance. Thus, corridor and stair lighting should use fluorescent or HID lamps. This is also important in locations where relamping is difficult, as in high-ceiling rooms such as gyms and assembly rooms.
4. In calculating illuminance, low light loss factor (LLF) values should be used to allow for aging of paints and dirt accumulation. Cleaning of lighting fixtures in schools is virtually unknown. An LLF value of 0.5 is reasonable. This being so, provision should be made to reduce initial overlighting or to provide for lumen maintenance.

5. Many schools are not air-conditioned. With the masking effect of air noise absent, careful control must be exercised over noise and vibration from ballasts, luminaire diffusers, and so on. Electronic ballasts are preferred if the construction budget tolerates the additional cost. Ballast noise increases with current rating. Therefore, 800-mA, high-output and 1500-mA, very-high-output lamps must be used with caution, particularly in locations that amplify sounds, or where low noise criteria (NC) obtain.
6. Lighting equipment must be designed for absolutely minimum maintenance, and those fixtures within easy reach should be vandal-proof. This means using captive screws, rust-preventive plated parts, captive-hinged diffusers whose cleaning requires only one person, ballast replacement without demounting fixtures (plug-in ballasts are available), nonyellowing plastics, and high-quality finish and assembly.

For recommended illuminances for the various visual tasks in an educational facility, see Sections 13.24 to 13.26 and IESNA RP-3-13, *Standard Practice on Lighting for Educational Facilities*. In the following sections, we discuss the lighting requirements of specific school building areas.

17.9 GENERAL CLASSROOMS

The classroom is the basic space in a school. Unlike the classic schoolroom with fixed seats, a single viewing direction, and a fixed teacher location, many modern classrooms, at all grade levels, utilize multiple-student groups, teacher mobility, multiple tasks in the same overall space, and movable seating arrangements. Such spaces require:

1. Controls that permit subdivision of lighting, and level control within the subdivision (see Sections 16.13–16.15).
2. A lighting system with an appreciable indirect component and good diffusion to minimize the problem of veiling reflections due to viewing direction (see Sections 13.27–13.32).
3. Low-brightness luminaires with high visual comfort probability (VCP) in all viewing directions, inasmuch as a considerable portion of the students' time is spent in a head-up position (see Section 13.28).

In addition to these special recommendations, some lighting recommendations applicable to all classrooms are:

4. Classrooms with digital displays require special lighting (see Section 17.19).
5. Generally, fluorescent luminaires should use T8 triphosphor lamps with a correlated color temperature (CCT) of 3500 to 4100 K and high color rendering indices (CRI). Electronic ballasts are preferred. Incandescent sources should not be used. Daylight, to the maximum extent, is desirable. Some form of daylight compensation is mandatory.
6. In comparing the costs of alternative appropriate lighting systems, use life-cycle costing techniques only, because these facilities are nonprofit and long-term. See Appendix J for an explanation of the principles of economic analysis. Use a computer program to perform the economic analysis where possible. Do *not* compare costs on the basis of footcandles (lux) per dollar (i.e., by dividing maintained illuminance by cost), because this leads to a preference for higher illumination levels and, consequently, higher energy usage.
7. Illuminance recommendations (see Section 13.26, Table 13.7 and IESNA) are divided by application type (e.g., accenting, administration, auditoriums, building entries, classrooms, dormitories, reading and writing, transition spaces, and so on) and further divided by task (type of work), visual age of observers, and orientation of the task (horizontal or vertical).

Figure 17.7 shows a perimeter classroom lighting layout using a two-lamp T8 louvered luminaire, and calculated initial horizontal and vertical illuminance values. A single-lamp version of the luminaire and its photometry are shown in Fig. 17.8. Note the crosswise batwing distribution that assists in limiting reflected glare.

17.10 SPECIAL-PURPOSE CLASSROOMS

(a) Shops

In classroom-shops, where at least half of the people using the space are 25 years old or younger (visual age), the illuminance target for machine

Fig. 17.7 *Computer-generated image of a 24-ft-W × 28-ft-L (7.3-m by 8.5-m) classroom using a perimeter layout of 16 4-ft (1.2-m) luminaires in a 14-ft × 22-ft (4.3-m by 6.7-m) rectangle suspended 18 in. (457 mm) from the ceiling and 9 ft (2.7 m) above the finished floor (AFF). The luminaires use T8 triphosphor lamps and high-frequency electronic ballasts. Average horizontal luminance on the desks is 74 fc (800 lux), and average vertical luminance on the chalkboards is 39 fc (420 lux). Room power density is 1.8 W/ft² (19 W/m²). (Courtesy of Zumtobel-STAFF Lighting Co.*

(*a*)

ZX-ST 1/32W T8
BIVERGENT STEPPED VANE LOUVER

Total Luminaire Efficiency 65%

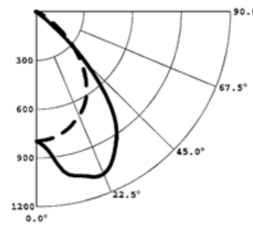
0% Uplight 100% Downlight

Spacing Criteria

Lateral Plane	0	90
	1.2	1.5

TOTAL LAMP LUMENS = 2900
INPUT WATTS = 32

Candela Distribution



Vertical Angle	Horizontal Angle 0	45	90	Zonal Lumens
0	797	797	797	
5	790	846	861	82.2
15	748	929	1043	256.4
25	670	917	1059	412.3
35	541	851	861	486.6
45	363	590	425	400.2
55	170	245	29	184.6
65	53	42	4	45.9
75	20	13	2	15.5
85	6	0	1	3.6
90	1	0	0	

Luminance Data in Candela / Sq. Meter

Angle in Vertical	Average 0	Average 45	Average 90
45	2763	4491	3235
55	1595	2299	272
65	675	535	51
75	416	270	42
85	371	0	62

Coefficients of Utilization

Effective Floor Cavity Reflectance = 20%

pcc	0.8				0.7				0.5			0.3		
pw	0.7	0.5	0.3	0.1	0.7	0.5	0.3	0.1	0.5	0.3	0.1	0.5	0.3	0.1
0	78	78	78	78	76	76	76	76	73	73	73	69	69	69
1	73	71	69	67	71	69	67	66	67	65	64	64	63	62
2	68	64	61	58	67	63	60	57	61	58	56	59	56	55
3	63	58	54	50	62	57	53	50	55	52	49	53	51	48
4	59	52	48	44	57	52	47	44	50	46	43	49	45	43
5	55	48	43	39	53	47	42	39	46	42	39	45	41	38
6	51	44	39	35	50	43	38	35	42	38	35	41	37	34
7	48	40	35	31	46	39	35	31	38	34	31	38	34	31
8	44	37	32	28	43	36	31	28	35	31	28	35	31	28
9	42	34	29	26	41	33	29	26	33	28	26	32	28	25

(*b*)

Fig. 17.8 *(a) This luminaire uses a very-high-reflectance silvered reflector and an unusual stepped mirrored baffle that provide low brightness for direct glare control, a batwing crosswise distribution for reflected glare control, and a sparkle on each baffle step for interest. (b) Photometrics of the luminaire shown in (a). (Courtesy of Zumtobel-STAFF Lighting Co.)*

TABLE 17.3 Illuminance Levels for Safety[a]

Hazard Requiring Visual Detection:	***Slight***	***Slight***	***High***	***High***
Normal Activity Level:	**Low**	**High**	**Low**	**High**
Areas	Normal classrooms Lounges Small offices Dorm rooms Washrooms	Shops Business classrooms Large offices Corridors Drafting rooms Lecture rooms Large classrooms Parking area Exterior walkways	Stairs Libraries Reading rooms Cafeteria Swimming pools Locker rooms Interior sports Bleachers	Boiler rooms Auditoriums Exits Exitways Laboratories Kitchens
Lux (footcandles)	5.4 (0.5)	11 (1.0)	22 (2.0)	5.4 (0.5)

Source: IESNA RP-3-1988; reproduced with permission.

[a]Minimum illuminance for safety or personnel, absolute minimum at any time and at any location where safety is related to seeing conditions.

work, inspection, assembly, and woodwork is 500 lux. Another aspect of lighting design in shops that does not exist to the same extent in other school environments is that of safety lighting (see Table 17.3, retained from an earlier IESNA report for its emphasis on safety).

(b) Music Rooms

The illuminance targets from IESNA again provide recommendations for both horizontal (150 lux, <25 visual age of observer) and vertical surface illuminance (100 lux, <25 visual age of observer). Specific applications will depend on orientation of music scores, which are normally held in the vertical position. Direct–indirect luminaires provide a high degree of diffusion that is helpful in this regard. For all spaces with vertical tasks, a computer analysis of the design is recommended to determine compliance with recommendations.

(c) Art Rooms

The primary requirement here is for constant-color daylight. Thus, north windows and skylights are highly desirable. For electric lighting, because color is so important, high-CRI fluorescent lamps are required. General illumination should be augmented by user-adjustable supplementary lighting. If use of models is anticipated, adjustable accent fixtures are advisable. For display of artwork, adjustable wall illumination is required. Ceiling track-mounted units are an excellent choice (see Figs. 17.2 and 17.9).

17.11 ASSEMBLY ROOMS, AUDITORIUMS, AND MULTIPURPOSE SPACES

The varied activities in these rooms make flexible lighting imperative. For performances, low-level dimmed incandescent lighting is required. Here, incandescent lamps are the recommended source because of the lower cost of dimming and the short burning periods. For assembly rooms, this can be augmented by architectural elements along walls and draperies and in the ceiling. For study, additional ceiling fluorescents or HID units can be switched on. The possible combinations are numerous; the different usages are the critical concern (Figs. 17.10 and 17.11). Acoustic concerns are acute because of the low NC criteria. Thus, electronic ballasts for HID sources as well as fluorescents should be used.

An additional consideration is step lighting. These units should be mounted to the side, or in risers, to illuminate the tread, and particularly its leading edge. Stage lighting is too highly specialized to be discussed here. Some form of stage lighting is required, however, and the building designer is advised to consult a theater lighting designer.

Fig. 17.9 *Art exhibition room illustrating good and bad lighting techniques. The upper wall fenestration is excellent for deep daylight penetration. Track lighting is ideal for display of art. The use of incandescent downlighting for general lighting is excessive and an eyesore. Also, the positioning of the track fixtures can create both direct and reflected glare problems and annoying shadows unless the sources are selected properly and ceiling height is at least 10 ft (3.1 m).*

Fig. 17.10 *Schools frequently utilize spaces for multiple functions. This space, typically used as a banquet room, doubles as an assembly room. High-intensity, recessed downlights in combination with large pendants provide sufficient light for both uses. (© Karen Tse; used with permission)*

Fig. 17.11 *Institutional cafeteria illuminated by cove lighting and daylight, accented with downlights and suspended pendants in a double-height space. Lighting is even, glare-free, soft in quality, and pleasant, yet of sufficient intensity to permit using the cafeteria as a working-meeting space. (© Karen Tse; used with permission)*

17.12 GYMNASIUM LIGHTING

Gyms present a situation similar to auditoriums in that they have widely varying usages. All fixtures should be sturdy and guarded. Phosphor-coated mercury, high-pressure sodium (HPS), and high-CRI metal–halide are excellent choices for color, life, control, and efficacy. Multiple lighting levels should be available by switching or dimming. For dance and social events requiring low-level general lighting, other fixtures can be provided with long-life incandescent or tungsten–halogen lamps, which provide good color for low-intensity lighting as well as illumination during HID startup or restart after an outage. All fixtures should be designed for relamping from the floor. Locker rooms should use guarded-strip fluorescents.

17.13 LECTURE HALL LIGHTING

Lecture hall lighting is similar, with respect to sources and other considerations, to illumination for classrooms. Adjustable-level fluorescent lighting is necessary for demonstrations, videos, and the like. Auxiliary lighting for demonstration tables and chalkboards completes the design. High-ceiling installations can utilize metal–halide for general lighting. Controls for lighting should be located at the demonstration table (Fig. 17.12).

17.14 LABORATORY LIGHTING

Laboratories differ from classrooms in that tables are fixed, bench surfaces are frequently very dark, many of the items used exhibit specular reflection, vertical surface illumination is important, and visual tasks are not normally prolonged or severe. With low ceilings, use direct fixtures with an uplight component run crosswise to the tables. Luminaires with a batwing distribution minimize reflected glare from specular equipment. If the ceiling height is sufficient, indirect lighting is highly desirable for the same reason. Indirect lighting also provides a high degree of diffuseness necessary for vertical surface illumination. See Fig. 17.13 for suggested layouts.

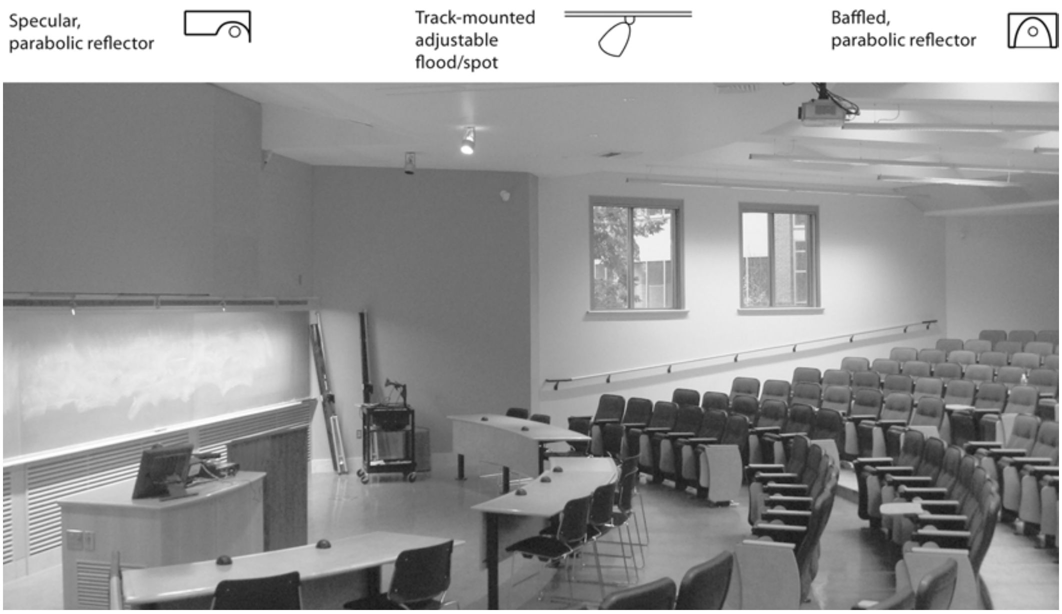


Fig. 17.12 *Typical lecture room lighting utilizes 45° cutoff baffled parabolic reflector troffers for minimum direct and reflected glare, adjustable track lighting for demonstration table illumination, and an asymmetric reflector for chalkboard lighting. The large display area on the front wall of the room will not experience veiling reflections with the illustrated lighting arrangement.*

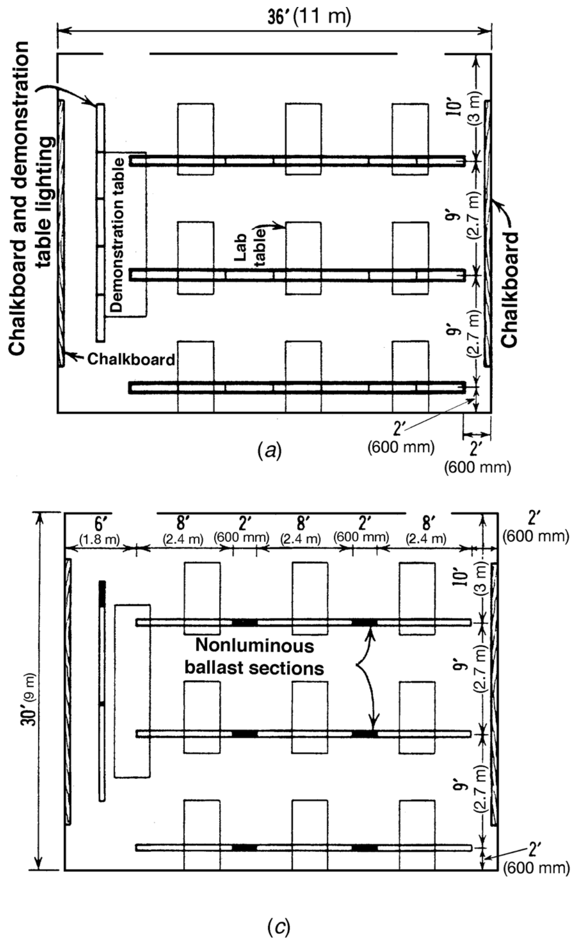


Fig. 17.13 *Laboratory lighting schemes. Running fixtures across tables or in aisles is preferable to fixtures in the transverse direction, in terms of reflected glare. (a) Pendant direct–indirect units. (b, c) Variations of the single semi-direct high-output (HO) design.*

17.15 LIBRARY LIGHTING

Libraries comprise several different seeing tasks, each of which requires its own lighting solution.

(a) General Reading Room

Here two solutions are possible, and both are commonly used. In the first, general lighting is supplied over the entire area, which is sufficient for reading tasks. For this purpose, fluorescent or metal–halide sources are normally applicable, the latter with ceiling heights of at least 10 feet (3 m). The long life and high efficacy of these sources are suited to the long burning hours found in libraries. The second and more energy-efficient solution involves low-level general lighting supplemented by local reading lighting on the tables or in carrels. This solution is consonant with task-lighting orientation and is preferred. Reading lighting should be fluorescent, user-adjustable if possible, and arranged to avoid veiling reflections when not user-adjustable.

Wherever HID sources are used, an instant restart source must be available to supply minimal lighting after an outage. Many commercial HID luminaires contain a small tungsten-halogen source for this purpose. Ballast noise can be a

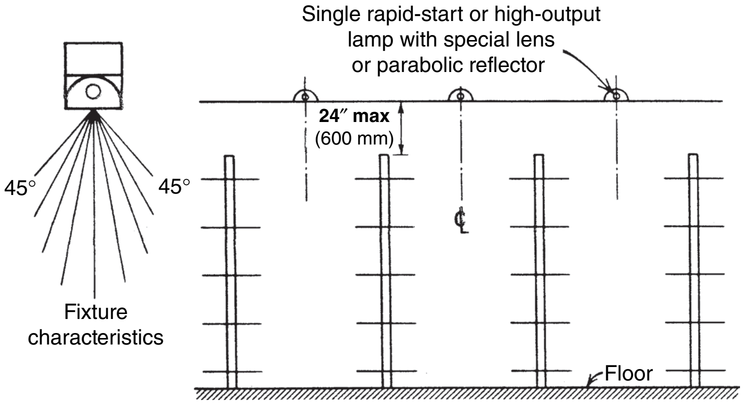


Fig. 17.14 *Stack lighting is best accomplished by fixtures with lenses specifically designed for the purpose. Fixtures with baffles and plastic diffusers generally do not give adequate vertical surface illumination.*

problem in low-NC spaces such as libraries. Electronic ballasts for fluorescent and HID sources are available and should be employed.

(b) Stack Areas

Here the required vertical surface illumination is best supplied by a special fluorescent unit designed for this purpose. These are mounted between stacks, and no higher than 24 in. (0.6 m) above them, for best results (Fig. 17.14).

17.16 SPECIAL AREAS

Most schools contain areas devoted to functions not covered previously. Some lighting recommendations for a few of these areas are as follows:

1. *Spaces where color rendering and color matching are important*, such as sewing rooms and textile and art work spaces, must be lighted with particular attention to illuminant color. Consistent color rendering without disturbing

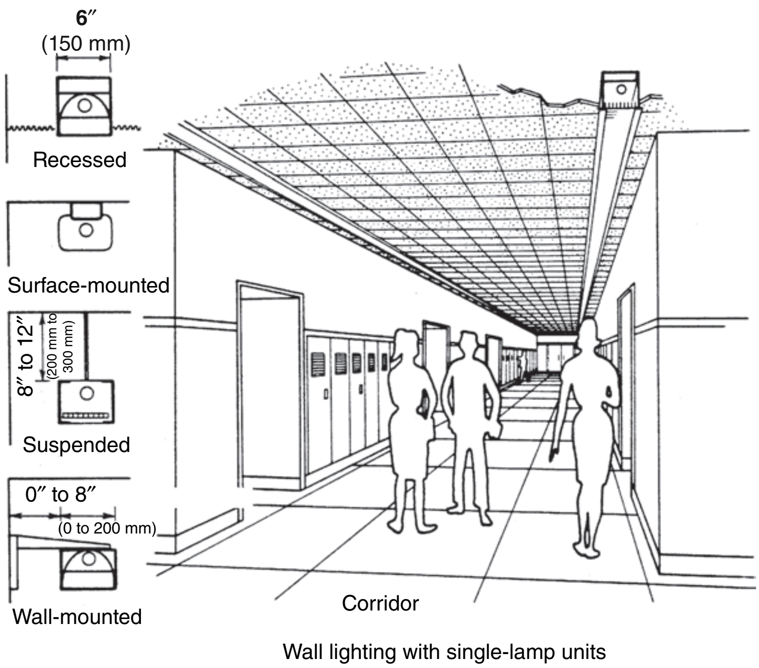


Fig. 17.15 *Lighting of school corridors. High-reflectance walls, floor, and ceiling improve utilization of light and increase the feeling of cheerfulness. The lighting technique illustrated is appropriate for school corridors. The rows of luminaires at each sidewall illuminate bulletin boards, special displays, and the faces and interiors of lockers more effectively than do units centered in the ceiling.*

metamerisms requires a continuous-spectrum source such as incandescent (including tungsten-halogen) and, of course, daylight.

2. *Food service areas* must be well lighted to emphasize cleanliness and food attractiveness. Color rendering of food is particularly important to enhance its appetizing appearance. Use 3100 K fluorescent or metal–halide lamps in preparation and serving areas, and eating areas, but in the latter at lower illuminance levels.
3. *Medical attention spaces* require high-illuminance, good color rendering lighting for diagnosis and conventional office lighting for records and desk tasks.
4. *Offices, storage spaces, industrial spaces, and outdoor facilities* have the same requirements as similar spaces in other buildings and are covered in the discussion that follows.
5. *Corridors and stairways in all types of buildings* require special lighting. Corridors intended only for circulation need be lighted to only ±10 fc (100 lux) unless a specific seeing task requires higher levels—for example, bulletin boards and lockers (Fig. 17.15). Lighting can also be used to give direction by longitudinal arrangement. Wall-mounted or recessed wall lighting is particularly effective in corridors, providing walking illumination plus lighting for posters, bulletins, and so on. Fluorescent luminaires mounted across corridors, particularly when corridors are long, are effective in reducing the "tunnel" impression. Incandescent sources are not recommended because of their low efficacy, high maintenance, and frequency of relamping. Fluorescent and HID sources are also suggested for stairwells. Care must be exercised here, however, to avoid direct glare, which causes attention to shift from the stairs to the light source and may thereby create a hazard.

17.17 OTHER CONSIDERATIONS IN SCHOOL LIGHTING

(a) Controls

See Sections 16.13 to 16.17. Because schools operate for the most part on fixed time schedules and during daylight hours, lighting controls of the preprogrammed time-base and daylight compensation types are readily applicable. Other energy-conserving control strategies can be utilized as applicable.

(b) Safety Lighting

See Table 17.3 for recommended illuminance levels. As pointed out, designers must be aware of the requirements of all jurisdictional codes.

(c) Emergency Lighting

Local, state, and National Fire Protection Association (NFPA) codes establish minimum requirements. Exits must be clearly identified with lighted signs and a lighted path to these exits provided. As with safety lighting, it is not sufficient that average illuminance meet requirements. Illuminance in any given area must be free of large level differences, which can cause disabling glare, particularly in view of the relatively high adaptation levels of occupants' eyes immediately before a lighting outage.

COMMERCIAL INTERIORS

17.18 OFFICE LIGHTING: GENERAL INFORMATION

The following information applies primarily to offices in commercial buildings and secondarily to similar spaces in other occupancies, such as educational and industrial buildings. In the latter cases, the general remarks applicable to facilities of those types take precedence. The special problems associated with digital displays are discussed in Section 17.19. Task-ambient (nonuniform) lighting is covered in Sections 17.20, 17.21, and 17.22. The reader is referred to IESNA RP-1 (2012), *American National Standard Practice for Office Lighting*, for a full discussion of office lighting.

(a) Light Sources

In the interest of energy economy and good color, T8 3500 to 4000 K triphosphor linear lamps or equivalent CFL units are recommended, along with high-frequency electronic ballasts. HID can be used in indirect installations with sufficient ceiling height (minimum 9.5 ft [2.9 m] clear). Color-corrected HPS and metal–halide units of high CRI are both suitable.

Source color must be coordinated with the color scheme of room surfaces and furnishings. In areas with a large daylight contribution, the source correlated color temperature should be at least 4000 K. Incandescents may be used for storage areas, closets, and other short-burning-period uses, although more efficient options exist. Incandescent and tungsten-halogen track lighting is used to advantage to illuminate displays of all sorts.

(b) Illuminance Levels

These are discussed in Section 13.26 for the particular type of activity involved. See also Standard RP-1. Recommended reflectances for room surfaces are:

Ceiling	80% minimum
Walls	50–70%
Partitions	50–70%
Floor	20–40%
Desktops, furniture	25–45%
Window blinds	40–60%

In landscaped offices, the typical half-height partitions block 30% to 80% of the light from ceiling luminaires, depending on the furniture arrangement. It is therefore all the more important that partition finishes (including fabrics) be light-colored. It is also desirable to have upper-wall sections painted to match the ceiling—that is, with a lighter finish than the remainder of the wall. This serves the dual function of increasing ceiling cavity brightness, particularly with suspended fixtures, and increasing vertical illumination due to reflection from this surface.

(c) Vertical Surface Illumination

This is required for many visual tasks in offices, such as those involving files, desk drawers, card files, and copy stands. Large area luminaires and a high degree of diffuseness are desirable. This is especially true in large offices where wall reflections are absent. Light-finished furniture surfaces, luminaires that yield an illuminated ceiling, and high-reflectance floors are also helpful.

17.19 LIGHTING FOR AREAS WITH DIGITAL DISPLAYS

These devices, which include desktops, laptops, tablets, and so on, have become standard office items. While some hardware developments have been able to create matte, non-glare surfaces, there are still a considerable number of digital displays that have specular faces—creating a special problem for office lighting that can become the deciding consideration in selecting the lighting system. Simply stated, with such specular faces, the primary problem is to avoid reflection on the screen from any luminous source in the area, including luminaires, windows, illuminated walls, and even light-colored clothing. Any such reflection makes reading data on the screen difficult and sometimes impossible.

Generally, walls, floors, and furniture should be finished in low-chroma, low-value colors, with a maximum reflectance of 50%. Very dark and very light desktops are to be avoided because of excessive luminance ratios, and the latter also because of reflections. In general, the standard recommended maximum luminance ratios of 1:3 in the near field and 1:10 in the far field should be the design goal here as well.

17.20 OFFICE LIGHTING GUIDELINES

(a) Private Offices

In these spaces, a task-ambient approach is frequently appropriate because there is usually only one primary visual task location, with the remainder of the space devoted to circulation and storage. Often, sufficient illumination for the latter is supplied by spill light from the task area, particularly when the task fixture is a pendant unit with an uplight component, as seen in Fig. 17.16. In large rooms, provide downlighting in sitting areas and some type of wall illumination using wallwashers, sconces, or a recessed perimeter unit to brighten the often dark wood-paneled walls. Accent lighting is required for pictures and other displays.

(b) General Offices

The two basic approaches to general office lighting are a uniform layout that provides task-level

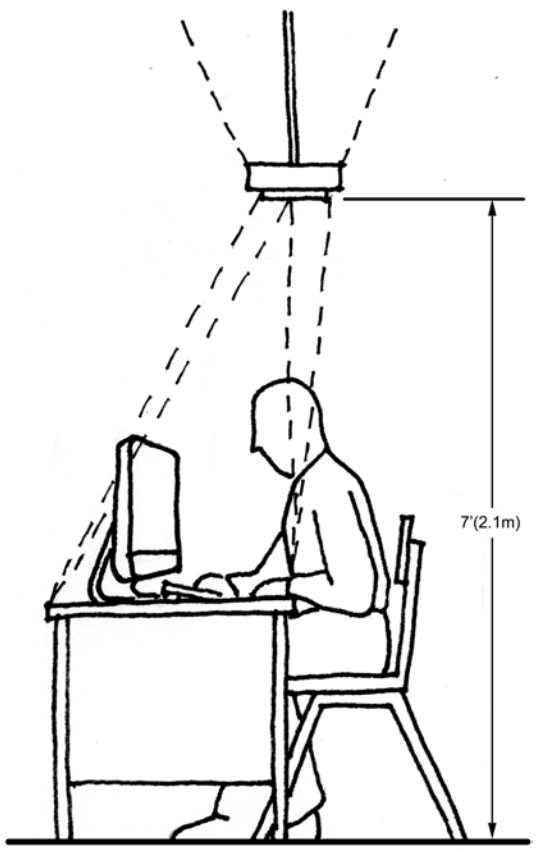


Fig. 17.16 *Geometry of a pendant task-ambient fixture. This unit is intended to supply not only task illumination, but also a measure of ambient lighting via its 20% uplight component. In a small room, this component is sufficient for general circulation. When installed as shown, veiling reflections are minimized and glare on the digital display is essentially eliminated.*

lighting in the entire area or a task-ambient design. The former, discussed in this section, is most appropriate to speculative-type construction, where the furniture layout is unknown but a complete job is required. (Frequently, however, the construction contractor provides only sufficient electric power for lighting and miscellaneous power; the lighting for the space is designed *after* the space has been rented as "tenant" work. In such cases, a task-ambient design is possible because tenant work is tailored to the user's needs.)

A task-illuminance overall layout is wasteful of energy and increases building energy budgets. Therefore, a uniform layout, when used, should be designed so that levels can be lowered easily in areas not requiring task lighting (see Sections 16.13–16.17). Furthermore, because no control of the geometry of direct and reflected glare is possible in such layouts, the luminaire selected must give minimum glare in *all* viewing directions. The system that best meets these requirements is one that uses a large number of low-brightness luminaires in a dense layout. This is a very expensive solution, however, unless the ceiling is either modular or coffered.

An interesting luminaire that creates a direct–indirect low-brightness unit in a troffer enclosure is shown in Fig. 17.17. Where the viewing direction is established but the exact furniture layout is unknown, a uniform layout with low-brightness parabolic reflectors with a batwing characteristic can be used to advantage, although a batwing distribution is generally not sought because of high direct glare and strong veiling reflections. Luminaire selection criteria for digital display areas were given in the preceding section. Where digital displays are not the overriding consideration, the following criteria are helpful:

1. In terms of appearance, a 2 ft × 4 ft (0.6 m × 1.2 m) fixture is appropriate in a 2 ft × 2 ft (0.6 m × 0.6 m) tile ceiling; a 1 × 4 ft (0.3 m × 1.2 m) fixture is suitable in a 1 ft × 1 ft (0.3 m × 0.3 m) ceiling; and a square 2 ft × 2 ft (0.6 m × 0.6 m) fixture is suitable in all tile patterns.
2. Two-inch-deep parabolic louvers permit a shallow fixture, but lamp shielding is poor. A 3-in. (76-mm) minimum louver depth is suggested for all large-cell parabolic louver luminaires.
3. Three-lamp parabolic louver units, which are usually too bright for digital display areas, can be used to advantage. Two-lamp units give better uniformity and VCP at a premium price.
4. Two-foot-square deep cell parabolics with 31-W T8 U lamps or biaxial compact lamps are an excellent choice in terms of VCP, uniformity of illumination, and appearance.
5. Premium-quality specular parabolic louvers that eliminate hot (bright) spots are available.
6. In relatively small offices with 1 ft × 1 ft (0.3 m × 0.3 m) ceiling tiles, 1-ft^2 (nominal 0.09-m^2) troffers with deep miniature parabolic wedge louvers and 16-W U lamps or compact fluorescents are an excellent all-purpose lighting solution (Fig. 17.18).

(*a*)

(*b*)

Fig. 17.17 *Luminaire construction giving a direct–indirect appearance (a) using a direct troffer construction (b). The medium-brightness luminaire interior reflects light, giving a deep, airy appearance. The translucent lamp enclosure maintains an acceptable luminance against the background (interior) reflector. The photometric characteristic is essentially circular in both longitudinal and transverse planes. (Courtesy of Zumtobel-STAFF Lighting Co.)*

7. Direct–indirect shallow luminaires with a wide, inverted batwing uplight distribution can be pendant mounted as low as 7.5 ft (2.3 m) AFF.

(c) Office Lighting Equipment

Office lighting equipment is generally not treated roughly. Fixtures with touch latches, light hinges, and adjustable devices may be selected without fear of breakage or vandalism.

Fig. 17.18 *One-foot-square (305-mm-square), 9-cell luminaire with deep parabolic louvers. This unit is applicable to small offices and/or areas with 1 ft × 1 ft (305 mm x 305 mm) ceiling-tile arrangements. (Courtesy of Zumtobel-STAFF Lighting Co.)*

(d) Maintenance

In most offices, maintenance is provided on a trouble-call basis. Lamps are replaced on burnout, and the fixture is then cleaned. Because of the long life of fluorescents and HID sources, this generally means a 3- to 5-year cleaning cycle. An LLF of 0.65 is reasonable in air-conditioned spaces; a lower LLF is appropriate in open-window offices.

(e) Fenestration

When fenestration is absent, a lighted valance around the room is recommended. This removes the wall-ceiling line and partially compensates for the lack of windows. It also brightens the walls and increases illumination on desks placed adjacent to the walls.

(f) Control

The control strategy (see Sections 16.13–16.17) should *minimally* provide (after tuning):

1. Daylight compensation
2. Possibility of operating individual small groups of fixtures while the remainder are off, to permit off-hours work
3. Path lighting through large spaces to permit traversing without turning on all lighting
4. Careful scheduling with supervised local override

With these general guidelines in mind, the following sections discuss specific topics in office lighting.

17.21 TASK-AMBIENT OFFICE LIGHTING USING CEILING-MOUNTED UNITS

Efficient modern office lighting, like other work-area lighting, is often predicated on a task-ambient design. This approach has the advantages of minimum contrast reduction at the task and minimum power use, the latter resulting in low operating cost. The method involves designing a uniform ceiling layout that provides low-level lighting for circulation and miscellaneous easy visual tasks, plus workstation-mounted task lighting. The latter can either be integral with the furniture (see the following section) or a separate, generally adjustable unit on or adjacent to the desk. The former is particularly useful for very severe seeing tasks when adjustability of angle and distance between light and work is vital. Integral furniture units are usually not adjustable, and are therefore limited to a maximum of about 750 lux on the task. Higher levels would generate excessive heat and, almost certainly, glare.

17.22 TASK-AMBIENT OFFICE LIGHTING USING FURNITURE-INTEGRATED LUMINAIRES

In lieu of ceiling-mounted luminaires to provide ambient lighting, indirect HID fixtures can be mounted on the top of furniture or can be free-standing. Task lighting would be integral with the office furniture. Advantages of this arrangement include the following:

1. The problem of furniture layout and layout changes is eliminated.
2. Initial construction cost is reduced.
3. Energy requirements are lowered because of short distances between light source and task.
4. Each occupant has on/off control of his or her task lighting, including, in some designs, positioning control.
5. Maintenance is greatly simplified because fixtures are readily accessible from the floor.
6. Floor-to-floor height can frequently be reduced.
7. Tax advantages normally accrue due to higher depreciation rates on furniture than on a building.

Disadvantages include the following:

1. Difficulty in dissipating heat and minimizing magnetic ballast noise due to proximity of sources to the user. For this reason, electronic ballasts should be used.
2. Veiling reflections are *always* present and can be severe.
3. Luminance ratios in the near and far surround may exceed recommended levels.
4. There may be difficulty in lighting a free-standing open desk, because most of the fixture types are undercounter or sidewall mounted.
5. The concentrating nature of the lighting units may cause difficulty in evenly lighting large tables or L-shaped desk areas.
6. This arrangement is not readily applicable to automatic switching and dimming schemes.
7. For satisfactory operation with fixed task lighting, the desk must be usable by both left- and right-handed people. This requires a considerable degree of duplication, as shown by lamps on both sides of the drawing in Fig. 17.19.

Figure 17.19 graphically shows the problem of local desk lighting. Experience suggests that only systems that permit user positioning adjustment of the light source have a high degree of user acceptability.

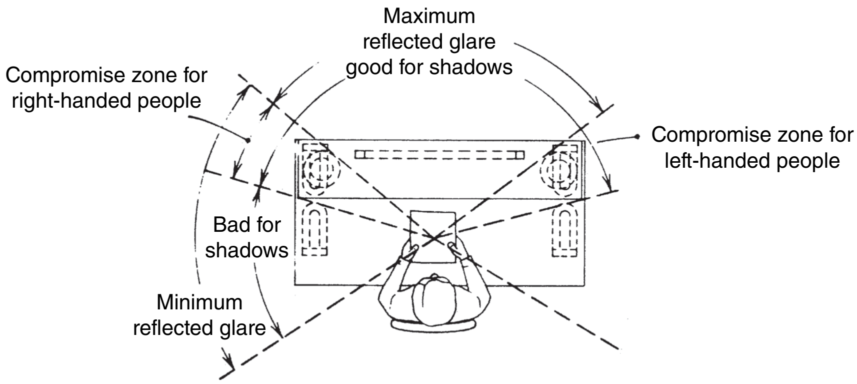


Fig. 17.19 *Furniture-mounted task lighting can create severe reflected glare or hand shadows if the luminaire location is not selected carefully. Further constraints are location in elevation (for shielding, needs to be low; for good distribution, needs to be high), appearance considerations, and compatibility with a worker's physical movements. Light source position adjustability removes most user objections to this type of task lighting.*

17.23 INTEGRATED AND MODULAR CEILINGS

The cost, appearance, and design-flexibility advantages of an integrated ceiling design over field-assembled and coordinated systems have long been known. As a result, ceiling systems with integrated lighting, acoustic control, and air-handling capabilities are commercially available in modular sizes (including 60-in. [1.5-m] square, 48-in. [1.2-m] square, and 30 in. × 60 in. [762 mm × 1524 mm]). Modules are made in flat and pyramidal shapes, the latter having several distinct advantages:

1. These modules are more interesting and aesthetically pleasing.
2. They offer more acoustic absorbency due to ceiling angles and a larger surface area.
3. The recessed center provides visual baffling, permitting the use of higher-brightness sources while maintaining high VCP.

Possible luminaire arrangements for both flat and pyramidal shapes are given in Fig. 17.20. In addition to the design flexibility available, an electrified track can be integrated into the system runners to supply both the lighting fixtures and power poles.

17.24 LIGHTING AND AIR CONDITIONING

The reduction of lighting power densities to below 2 W/ft^2 (21 W/m^2) in all but special areas considerably reduces the impact of lighting-generated heat on a building's HVAC system. In non-air-conditioned buildings, the lighting heat contribution is partially applicable to building heating. Fixture efficiency is directly affected by its temperature. Fluorescent units operate at an optimum temperature of 77°F (25°F). Temperatures above and below this decrease output and fixture efficiency. Thus, heat removal from units is desirable even at low lighting-energy levels. The most effective method of fixture heat removal is return air duct connection to the unit itself. This method is relatively expensive and immobilizes the fixture. Alternatively, the plenum can be exhausted with return air passing over the fixtures, picking up heat.

INDUSTRIAL LIGHTING

17.25 GENERAL INFORMATION

In industrial lighting, a primary design consideration is cost. Given acceptable standards of comfort and safety for the working staff, additional costs for lighting must be self-justifying economically. In one case, a good lighting installation was improved at considerable cost. Production jumped 15%, of which 3% was sufficient to amortize the cost of the lighting alteration. In another case, an outlay for new inspection lighting reduced product

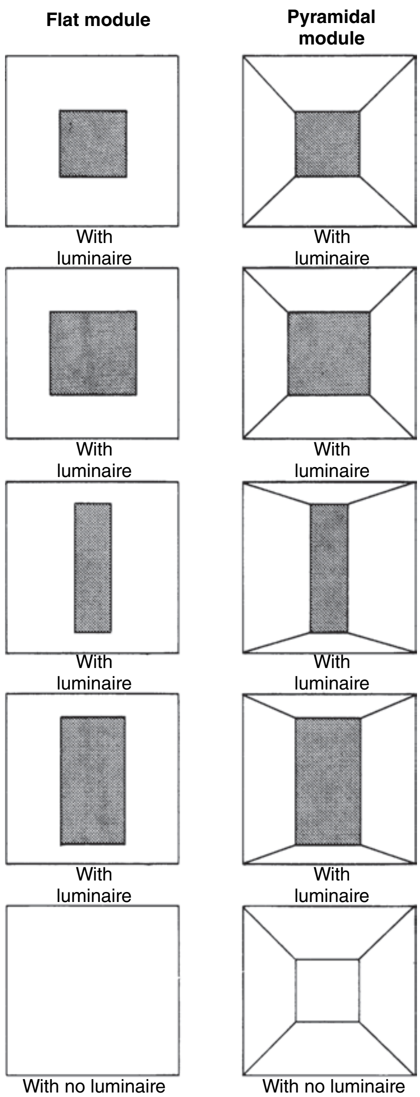


Fig. 17.20 *Various configurations of reflected ceiling plan modules.*

failures and proved economically sound. In a third, improved lighting reduced accidents, improved employee morale, and consequently improved production. The cases studied are far too numerous to mention; general principles are adduced instead.

17.26 LEVELS AND SOURCES

Illuminance requirements are detailed in Chapter 30 of the *The Lighting Industrial Handbook* (IESNA, 2011). The handbook describes in detail a method for determining illuminance values for specific industrial occupancies and tasks. Where levels higher than 50 to 75 fc (540 to 800 lux) are required, general illumination should be supplemented by task illumination. Industrial facilities lend themselves readily to daylighting because many are one-story structures. Thus, roof monitors, skylights, and clerestories are readily applicable and extremely desirable. However, inasmuch as industrial facilities are frequently sited in industrial areas with attendant heavy atmospheric soot and dirt, a frequent cleaning and maintenance program is necessary if the LLF is to be kept at reasonable levels. This observation is also applicable to indoor lighting systems.

Light sources for industrial applications should exhibit high efficacy, good lumen maintenance, and long life. Of the sources available today, fluorescent and HID lamps meet these criteria. Induction and sulfur lamps may join this group after additional development and field testing. Where color is not critical, HPS is the recommended source. Adaptation to its warm yellow color is rapid, and if it is mixed with metal–halide or mercury sources, no problem should be encountered. HID lamps are easier to maintain, store, clean, and relamp than fluorescent lamps and have equal or better efficacy, but have the disadvantages of delay and lower output on restrike. Because of their relatively small size, HID sources are used in focusing reflectors that produce intensity (cp) distribution characteristics designed for specific illumination objectives. Thus, HID sources are generally used for high-bay (>25 ft [7.6 m]) and medium-bay (15–25 ft [4.6–7.6 m]) installations. For low-bay lighting, industrial reflector fluorescent luminaires and low-bay HID reflectors are both applicable.

One of the most common industrial lighting tasks is warehouse aisle lighting that must provide adequate vertical surface illumination on racks on both sides of an aisle. The required cp distribution to perform this task efficiently is a modified batwing curve. This is more easily accomplished in low-bay lighting with a continuous row fluorescent installation than with discrete HID units.

17.27 INDUSTRIAL LUMINANCE RATIOS

For reasons explained in preceding sections, luminance ratios must be controlled. Recommendations are given in Table 13.7. In many situations it is difficult to control the surrounding brightness. Ceilings, which frequently are covered with piping, ducts, and other equipment, should be light. Therefore, this mechanical equipment must be painted with matte, light unsaturated colors; maintenance and cleaning must be good; and fixtures should have an upward component of light to avoid more than a 20:1 ratio of task-to-ceiling luminance.

Use of bright saturated colors for general surface painting should be avoided because they draw attention and frequently have special significance. In addition to color-coded piping (banding is preferable), red frequently means fire equipment; green, first aid; orange, danger; and so on. White is also to be avoided, being excessively bright and susceptible to dirt. Recommended minimum reflectances are:

Ceiling	75–85%
Walls	40–60%
Equipment	25–45%
Floors	20%

17.28 INDUSTRIAL LIGHTING GLARE

The problem of direct glare can be acute in low-bay installations, and that of reflected glare in high-bay designs, when either uses a point source. One method of reducing direct glare is the use of low-brightness prismatic lens units with a black reflector behind the lens. Methods of minimizing veiling reflection from all sources were discussed previously.

17.29 INDUSTRIAL LIGHTING EQUIPMENT

The cost of maintenance increases with labor rates. For this reason, high-quality lighting equipment yields the lowest owning and life-cycle costs. For instance, the cost of replacing a ballast for HID lighting units frequently exceeds the cost of the ballast. It is thus more economical to utilize long-life, high-quality ballasts, particularly where luminaires are not readily accessible.

Other suggestions for lowering costs, both initial and operating, include using ventilated luminaires that tend to be self-cleaning by convection (Fig. 17.21), in addition to giving the needed upward light component; using bus-mounted

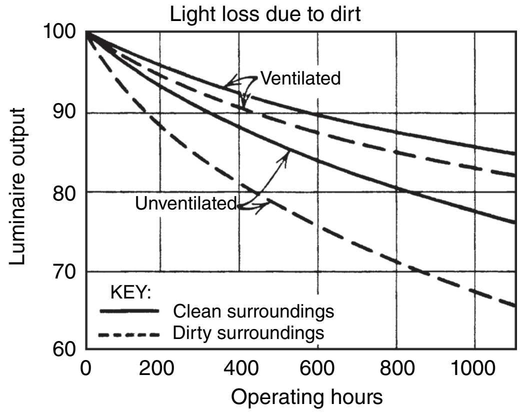


Fig. 17.21 *Graph demonstrating the advantage of ventilated fixtures.*

fixtures for rapid installation and repair; using lowering mechanisms on high-bay units, to avoid catwalk or platform relamping with a concomitant *extremely* high cost; using fixtures arranged for "stick" relamping from the floor in medium- and low-bay work; and generally incorporating modern equipment into the plant.

Proper maintenance is of paramount importance in industrial facilities because of the prevalence of dirt, vibration, and the overall wear-and-tear of the industrial environment. Maintenance includes cleaning, relamping, inspection, and preventive maintenance. Relamping on a burnout basis is extremely uneconomical because of disruption of production and lowered production due to lumen depreciation before burnout. Relamping should be done on a planned group basis. Similarly, if the specific facility has a high dirt accumulation rate, cleaning must also be done on a planned group basis rather than only at relamping time.

Ballast noise, including the high levels of HID ballasts, is not usually a factor in industrial facilities because of high ambient noise. In relatively quiet installations and/or where fluorescent fixtures are mounted a short distance above a work bench—as in inspection and fine assembly—this is not true, and electronic ballasts are needed.

17.30 VERTICAL-SURFACE ILLUMINATION

In industrial facilities more than any other occupancy, the illumination of vertical surfaces is crucial. This is a result of the nature of the work: machines, storage, gauges, and so on, all require high vertical-surface illuminance (Fig. 17.22). The illuminance on a vertical surface is the result of the horizontal component of the lighting. This is

$$\text{fc} = \frac{\text{cp}}{D^2}\sin\theta = \frac{\text{cp}\times R}{D^3} = \frac{\text{cp}\times\cos^2\theta\times\sin\theta}{H^2}$$

To maximize the horizontal component, we set to zero the derivative of fc with respect to θ. Thus

$$\frac{d\text{fc}}{d\theta} = \frac{\text{cp}}{H^2}(-2\cos\theta\times\sin^2\theta+\cos^3\theta) = 0$$

or

$$2\sin^2\theta = \cos^2\theta$$
$$\tan^2\theta = ½$$
$$\tan\theta = 0.707 = \frac{R}{H}$$
$$\theta > 35°$$

Therefore, maximum vertical illuminance (illumination resulting from the horizontal-lighting component) is obtained when the angle between the fixture's vertical axis and the work is approximately 35°. Hence, we should select a fixture whose candlepower distribution curve demonstrates a high value at that angle. Of course, the derivation is for a single location and fixture. For good vertical and angular illumination over a large area, arrange fixtures with considerable overlap.

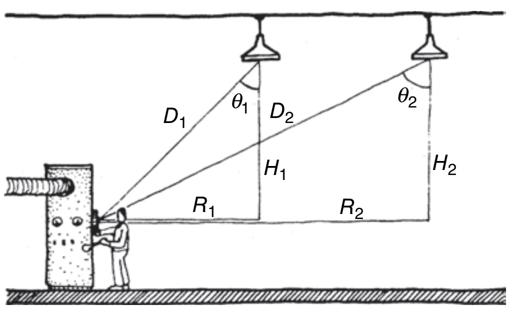


Fig. 17.22 *Vertical-surface illuminance is maximum where θ is approximately 35° (see derivation in text).*

SPECIAL LIGHTING APPLICATION TOPICS

17.31 EMERGENCY LIGHTING

Emergency lighting is required when the normal lighting is extinguished, which can occur for any of three reasons:

1. General power failure
2. Failure of the building's electrical system
3. Interruption of current flow to a lighting unit, even as a result of inadvertent or accidental operation of a switch or circuit disconnect

As a result of the third reason, sensors must be installed at the most localized level—that is, at the lighting fixture (voltage sensor) or in the lighted space (photocell sensor).

(a) Codes and Standards

Because emergency lighting is a safety-related item, it is covered by various codes, several of which may have jurisdiction. In addition, there are widely accepted technical society and industry standards whose recommendations normally exceed the minima required by codes.

1. *NFPA 101: Life Safety Code* (NFPA, 2012). This code defines the locations within specific types of structures requiring emergency lighting and specifies the level and duration of the lighting.
2. *NFPA 70: National Electrical Code* (NFPA, 2014). This code deals with system arrangements for emergency light (and power) circuits, including egress and exit lighting. It discusses power sources and system design.
3. *NFPA 99: Health Care Facilities Code* (NFPA, 2012). This code deals with special emergency light and power arrangements for these facilities.
4. *OSHA regulations.* These are primarily safety-oriented and, in the area of emergency lighting, discuss primarily exit and egress lighting requirements.
5. *Industry standards.* These include the publications of the IESNA and the IEEE, in particular IEEE Standard 446: *Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications* (IEEE, 1995).

Because codes and standards are constantly being revised and updated, the designer for an actual project must determine which codes have jurisdiction, obtain current editions, and design to fulfill their requirements. The following material provides general information and focuses on good practice, but is not intended to take the place of applicable construction and safety codes.

(b) Minimum Illumination Levels and Duration of Emergency Lighting

Most codes and authorities require a *minimum average illuminance at floor level*, throughout the means of egress, of 1.0 fc (10 lux). This is considered sufficient, after eyes accommodate, to permit orderly egress. No point along the path of egress should have an illuminance of less than 0.1 fc (1 lux), and the maximum-to-minimum ratio of illuminances along the egress path should not exceed 40:1. The language of the codes is precise, and the consequences must be completely understood in order to properly design an emergency lighting system.

The NFPA *Life Safety Code* relates to life safety—that is, safe egress during an emergency that often involves fire. In such instances, smoke normally obstructs vision at eye level, and it is therefore extremely important that the required illumination be available at floor level. Ceiling-mounted emergency lighting may not illuminate the floor in smoky areas and may even worsen a situation by creating a bright, fog-like condition. It is therefore widely recommended that adequate egress lighting be provided at *baseboard level*. Some codes already mandate baseboard egress lighting. The requirement that the *average minimum* illuminance be 1.0 fc (10 lux) along with the mandated minimum of 0.1 fc (1 lux) at any point and a maximum 40:1 ratio of maximum to minimum illuminance, should effectively eliminate faulty design that utilizes several widely separated bright sources.

Other authorities recommend that escape routes be lighted to not less than 1% of their normal illuminance, but in no case less than 0.5 fc (5 lux). Where the 1% of normal requirement recommendation falls below 1 fc (10 lux) (normal illuminance less than 100 fc), we suggest the 1-fc (10-lux) minimum required by the *Life Safety Code*.

Duration of the 1-fc (10-lux) level of emergency lighting is normally specified to be a minimum of 90 minutes (for egress) and 0.6 fc (6 lux) thereafter. Facilities that cannot be evacuated quickly require higher levels for indefinite periods.

(c) Central Battery Emergency Lighting Systems

Generators are normally arranged to replace the utility service during outages, using the building's normal electrical distribution system, with the difference that only essential loads remain connected. This does not meet the requirement that emergency lighting be supplied on power failure, *even if the fault is local* (i.e., within the building).

Central battery systems are of three types:

1. *Systems supplying low-voltage DC (6 to 48 V) to dedicated emergency lighting units.* (See Fig. 17.23*a*.) This type of central battery installation consists of a battery, charger, and switching equipment. The emergency lighting units are generally not part of the normal lighting system, consisting instead of dedicated incandescent fixtures. The system has the same limitation as a generator, and therefore is not applicable to most emergency lighting situations except when equipped with multiple downstream sensors. As such sensing would be highly uneconomical, this system is limited to a single (large) space with common outage sensing. This arrangement has the further disadvantage that the emergency lighting units may intrude on the building's decor and architecture, inasmuch as they are not part of the normal lighting system. Also, because the lighting units are isolated devices, it is difficult to obtain a satisfactory degree of emergency illumination uniformity, as explained previously. See also Section 17.31*e*).
2. *Systems supplying 120-V DC*. (See Fig. 17.23*b*.) This arrangement supplies line voltage DC to emergency lighting fixtures, which are also used as part of the normal system. HID and fluorescent luminaires are furnished with integral inverters to change the incoming DC to AC. This arrangement has the advantage of a central, well-maintained battery supply, but the disadvantage of requiring a full DC distribution system.
3. *Systems supplying line voltage AC*. (See Fig. 17.23*c*.) Here the central unit contains a

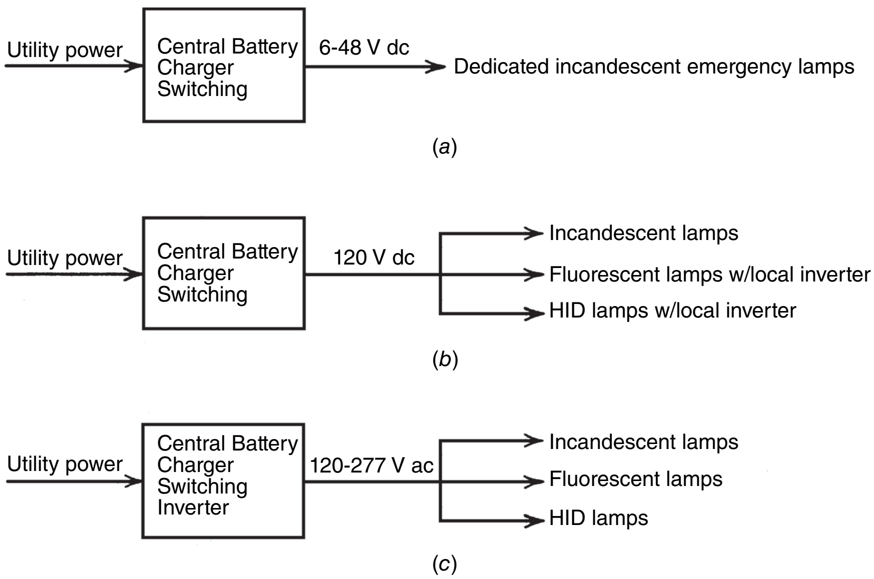


Fig. 17.23 *Schematic diagrams of an emergency power system using central batteries. In (a) the emergency system is completely separate from the normal lighting system and utilizes dedicated lighting units. (b) This arrangement furnishes DC to the luminaire, where it is inverted to AC (except for incandescent lamps). The fixtures are utilized during both normal and emergency operation. As switching is instantaneous, HID lamps are not extinguished. (c) An arrangement that is similar to (b) except that a central inverter supplies AC continuously. Here, too, the lamps are used in both normal and emergency modes.*

battery, charger, central DC/AC inverter, and switching equipment. Such a system can supply power to incandescent, fluorescent, and HID systems in spaces where a single voltage-loss sensing point is sufficient. The emergency lighting units are part of the normal lighting system. This arrangement is most frequently used where a distributed system with local batteries (discussed later) would not be readily applicable due to the size of the load, as would be the case with high-wattage HID luminaires. A typical 10-kVA on-line UPS cabinet designed to supply emergency AC power to HID lamps measures approximately 40 in. × 50 in. × 20 in. (1.0 m × 1.3 m × 0.5 m) and weighs about 1000 lb (450 kg).

(d) Distributed (Local) Emergency Lighting Arrangements

As a result of the inability of a central system to respond to a localized outage, a frequently used emergency lighting arrangement is one in which the source of power, as well as all the voltage-sensing and voltage-switching equipment, is installed at the emergency lighting fixture, which is usually part of the normal lighting system. The emergency pack consists of a rechargeable battery and charger, voltage-sensing and voltage-switching equipment, and, in the case of fluorescent lamps, an electronic package (ballast) that operates the lamp at high frequency and generally at reduced output (Fig. 17.24). These packages, which are designed to supply the code-required 90 minutes of emergency lighting, are maintenance-free for periods of up to 5 years. A second type of distributed emergency lighting unit is the familiar packaged unit with integral incandescent lamps. Several designs are shown in Figs. 17.25 and 17.26.

(e) Emergency Lighting Design Considerations

The levels and duration discussed in Section 17.31*b* refer only to egress lighting. However, general emergency lighting is required to avoid distress and even panic that unfortunately may rapidly ensue. The required emergency illuminance in specific areas should be related to the area's normal illuminance

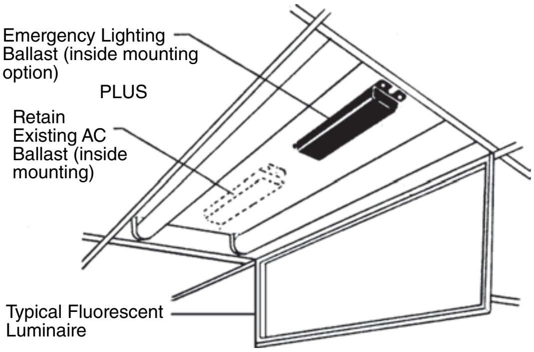


Fig. 17.24 The emergency lighting ballast package contains a 90-minute-capacity high-temperature battery, inverter, sensing and switching equipment, and electronic ballast circuitry to operate the lamp(s) at full or reduced output. The emergency ballast is energized on loss of normal power. The entire package measures 9½ in. × 2⅜ in. × 1½ in. (241 mm x 60 mm x 38 mm). (Courtesy of Big Beam Emergency System, Inc.)

and the degree of hazard in the area. Therefore, we would suggest:

Exit area	5 fc (50 lux)
Stair	3.5–5 fc (35–50 lux)
Hazard areas, such as machinery room	2–5 fc (20–50 lux)
Other spaces	1.0 fc (10 lux)

These levels should be essentially uniform. When the illuminance in an interior space drops instantaneously from 30–100 fc (300–1000 lux) to 1–5 fc (10-50 lux), the eyes require up to 5 minutes to fully accommodate. During this long period, occupants are partially sightless—a condition that lends itself readily to panic. For this reason, bright, spotlight-type heads must be *very carefully arranged*. Otherwise they can create disabling glare and distorting shadows and impede eye accommodation.

Although it is customary to furnish the required emergency illumination from ceiling- or wall-mounted fixtures, consideration must be given to the code requirement, as noted in Section 17.31*b*, that specified emergency lighting levels be maintained at floor level. Because heavy smoke can readily obscure light from overhead fixtures, it is advisable to install some (preferably directional) emergency lighting fixtures near floor level.

(f) Exit Lighting

Most codes require 5 fc (50 lux) on nonilluminated exit signs, internally illuminated signs with the same visibility as an externally illuminated sign, or self-luminous signs with a specified luminance (usually at least 0.21 cd/m^2). Some exit signs are equipped with a battery and controls that provide 1½ hours of illumination on loss of utility power. Others are arranged to illuminate the exit area

(*a*)

(*b*)

Fig. 17.25 Commercial emergency lighting units. (a) This decorative unit contains a sealed, maintenance-free lead–acid battery, an automatic charger, and an automatic low-battery-voltage disconnect. The battery is designed to supply a minimum of 90 minutes of operation of two fully adjustable 5.4-W sealed beam lamps. The unit measures 16.5 in. × 5 in. × 5 in. (419 mm x 127 mm x 127 mm). (b) Conventional design emergency unit contains a lead–acid or lead–calcium battery, which is housed with its required electronic control and safety equipment in a polycarbonate housing. The lamps are rated 7.2 W each. The entire unit measures approximately 15.75 in. × 11.5 in. × 4 in. (400 mm x 292 mm x 102 mm); exact dimensions vary with battery type, voltage, and capacity. (Courtesy of Dual-Lite, a division of Hubbell Lighting, Inc.)

Fig. 17.26 Industrial-type emergency lighting units. (a) This unit has a maintenance-free, lead–acid battery. The cabinet conforms to NEMA Type 3R enclosure requirements. The unit can be arranged to supply an additional two remote 12-W sealed-beam heads. The unit measures 13 in. × 6.75 in. × 17 in. over the lamps (330 mm x 172 mm x 432 mm), and is provided with an external charge indicator light and a test switch. (b) This compact thermoplastic polycarbonate enclosure unit is sealed and gasketed for rugged industrial application. It measures approximately 10 in. × 11 in. × 16 in. (254 mm x 280 mm x 406 mm) and contains the usual electronics for control and charging of its lead–acid battery. A charge indicator and a test switch (to simulate power failure) are mounted on the side. (Courtesy of Dual-Lite, a division of Hubbell Lighting, Inc.)

beneath the sign (Fig. 17.27), and still others are equipped with a flasher and/or an audible beeper that assists people in finding the exit in a light-obscuring, smoke-filled room. Finally, some exit signs are nonelectrical self-illuminating, requiring continuous illumination, and are part of the emergency lighting system.

17.32 FLOODLIGHTING

Floodlighting, both interior and exterior, is used extensively for the diverse locations listed in Table 17.4, in addition to the more common sports facility lighting, which is not listed. At the designer's disposal are a variety of sources with respect to output, color, life, efficacy, and wattage (see Chapter 14).

Although a detailed floodlighting design involves complex calculations beyond the scope of this book, it is often sufficient for the designer to utilize a watts-per-square-foot table such as Table 17.4 to determine the approximate floodlighting requirements. The designer should also consult the unit power allowances for exterior lighting listed in ANSI/ASHRAE/IESNA Standard 90.1.

Thus, if one is concerned with lighting a self-service parking lot at a neighborhood shopping center, and metal–halide is selected, Table 17.4 tells us that approximately 0.055 W/ft^2 (0.6 W/m^2) will suffice. This is well within the limits of Standard 90.1. If the lot is 200 ft × 500 ft (100,000 ft^2), then 0.055 W/ft^2 × 100,000 ft^2 (5500 W) is required. This figure is a good first estimate. The actual power level depends upon the specific equipment and design. This may vary from the initial estimate by ± 20%.

The arrangement and choice of equipment must be determined before the problem can be considered solved. Considerable assistance on this score can be obtained from either the lighting engineer involved or from representatives of equipment manufacturers.

Although most floodlight installations use a single type, the installation shown in Fig. 17.28*b* used a combination of metal–halide and mercury to obtain the desired effect.

Fig. 17.27 *Typical application of an exit light with a built-in battery, charger, and controls. Note that the bottom of the unit is designed to illuminate the area immediately in front of the exit.*

17.33 STREET LIGHTING

Although detailed street-lighting calculations and design considerations are beyond the scope of this book (see appropriate IESNA guidance), a few remarks are in order. New installations now use HID sources almost exclusively. The low efficacy and short life of incandescent sources and the bulkiness of linear fluorescents make them obsolete. Furthermore, high street-lighting levels reduce vandalism and crime, improve night merchandising, and add to an area's attractiveness. A walkway luminaire (with light pollution potential) is shown in Fig. 17.29.

17.34 LIGHT POLLUTION

A frequently neglected corollary to the principle of placing light where it is required is not to place light where it is not required. *Light pollution* is frequently defined as unwanted light in public places, whereas *light trespass* is the intrusion of unwanted light on private property. The latter includes light intrusion in windows and on private property, whereas the former covers excessive brightnesses everywhere, plus stray light that finds its way into the night sky, to the distress not only of astronomers, but also of anyone who simply wishes to enjoy the beauty of a star-filled sky. At this writing, no standards exist that define the light levels that constitute an intrusion or a nuisance glare. However, a few simple guidelines can assist the designer in avoiding the creation of a nuisance:

1. Light all exterior vertical surfaces from above, not below, wherever possible. This reduces skylight pollution.
2. Use luminaires with sharp cutoff beyond the illuminated area. Shields can be added to standard luminaires to accomplish this.
3. After an installation is complete, inspect it at night to determine whether any nuisance has been created.

Further information on this subject can be found in IESNA technical memoranda TM-10-00 and TM-11-00, dealing with light trespass.

17.35 REMOTE-SOURCE LIGHTING

Every experienced lighting designer has at some time felt the need for a remote-source luminaire to fill a specific lighting need. Among the most common situations are:

- Display lighting for light- and heat-sensitive objects such as old books, fabrics, drawings and paintings, and, in general, objects containing organic materials, dyes, and coloring. Of particular importance in this category is the acute sensitivity of such objects to UV radiation, which exists in daylight and light from most electrical sources.
- Installations where relamping is a major logistic and financial problem. These include high-ceiling auditoriums and public assembly spaces of all sorts, high-bay lighting areas and other difficult-access locations, clean rooms, spaces with security entry limitations, and rooms that cannot tolerate disturbances or interruptions,

TABLE 17.4 Lighting Application Guide

Application	Minimum Footcandles (lux) Maintained[a]		Watts per Square Foot (W/m²)[b] Generally Required: Tungsten–Halogen		Mercury		Metal–Halide		High-Pressure Sodium	
Automobile Parking										
Attendant parking	2 (20)		0.38 (3.8)		0.17 (1.7)		0.11 (1.1)		0.075 (0.75)	
Industrial lots	1 (10)		0.13–0.15 (1.3–1.5)		0.06–0.07 (0.6–0.7)		0.037–0.044 (0.4–0.5)		0.026–0.03 (0.26–0.3)	
Self-parking lots	1 (10)		0.13–0.15 (1.3–1.5)		0.06–0.07 (0.6–0.7)		0.037–0.044 (0.4–0.5)		0.026–0.03 (0.26–0.3)	
Shopping Centers										
Neighborhood	1 (10)		0.13–0.19 (1.3–1.9)		0.06–0.09 (0.6–0.9)		0.037–0.055 (0.4–0.6)		0.026–0.038 (0.3–0.4)	
Average commercial	2 (20)		0.26–0.3 (2.6–3.0)		0.12–0.135 (1.2–1.4)		0.075–0.087 (0.7–0.9)		0.052–0.06 (0.5–0.6)	
Heavy traffic	5 (50)		0.65 (6.5)		0.29 (2.9)		0.19 (1.9)		0.13 (1.3)	
Automobile Sales Lots										
Front row (front 20 ft [6 m])	50 (500)		10 (100)		4.5 (45)		2.9 (29)		2.0 (20)	
Remainder	10 (100)		1.5–1.8 (15–18)		0.68–0.81 (6.8–8.1)		0.44–0.52(4.4–5.2)		0.3–0.36 (3.0–3.6)	
Building										
Construction	10 (100)		1.5–1.8 (15–18)		0.68–0.81 (6.8–8.1)		0.44–0.52 (4.4–5.2)		0.3–0.36 (3.0–3.6)	
Excavation	2 (20)		0.26–0.3 (2.6–3.0)		0.12–0.14 (1.2–1.4)		0.075–0.09 (0.7–0.9)		0.052–0.06 (0.5–0.6)	
	Adj. Area									
Buildings up to 50 ft (15 m) High	**Light**	**Dark**								
Light surfaces	15 (150)	5 (50)	3.3 (33)	1.2 (12)	1.5 (15)	0.54 (5.4)	0.96 (10)	0.35 (3.5)	0.66 (7)	0.24 (2.4)
Medium light surfaces	20 (200)	10 (100)	4.3 (43)	2.2 (22)	1.94 (19)	1.0 (10)	1.25 (13)	0.64 (6)	0.86 (9)	0.44 (4.4)
Dark surfaces	50 (500)	20 (200)	10.0 (100)	4.3 (43)	4.5 (45)	1.94 (19)	2.9 (29)	1.2 (12)	2.0 (20)	0.86 (9)
	Adj. Area									
Billboards and Signs	**Light**	**Dark**								
Good contrast	50 (500)	20 (200)	10 (100)	4.3 (43)	4.5 (45)	1.94 (19)	2.9 (29)	1.25 (13)	2.0 (20)	0.86 (8.6)
Poor contrast	100 (1000)	50 (500)	20 (200)	10 (100)	9.0 (90)	4.5 (45)	5.8 (58)	2.9 (29)	4.0 (40)	2.0 (20)
Protective Lighting										
Gates and vital area	5 (50)		1.2 (12)		0.54 (5.4)		0.35 (3.5)		0.24 (2.4)	
Building surrounds	1 (10)		0.15–0.19 (1.5–1.9)		0.07–0.09 (0.7–0.9)		0.044–0.055 (0.44–0.55)		0.03–0.04 (0.3–0.4)	
Roadways										
Along buildings	1 (10)		0.24 (2.4)		0.11 (1.1)		0.07 (0.7)		0.05 (0.5)	
Open areas	0.5 (5)		0.08–0.1 (0.8–1.0)		0.036–0.045 (0.36–0.45)		0.023–0.029 (0.23–0.29)		0.02 (0.2)	
Storage yards	20 (200)		3.6–4.3 (36–43)		1.6–1.94 (16–19)		1.04–1.25 (10.4–12.5)		0.72–0.86 (7.2–8.6)	
Storage yards (inactive)	1 (10)		0.15–0.19 (1.5–1.9)		0.07–0.09 (0.7–0.9)		0.044–0.055 (0.44–0.55)		0.03–0.04 (0.3–0.4)	
Shopping Centers										
Parking areas (attraction)	5 (50)		0.65 (6.5)		0.29 (2.9)		0.19 (1.9)		0.13 (1.3)	
Buildings (attraction)					(See Buildings)					
Used car lots					(See Automobile Parking)					

[a]All illuminance levels for ground area applications are *horizontal* values.

[b]SI conversions are approximate, using a factor of 10 (versus 10.76).

(*a*) (*b*)

Fig. 17.28 *(a) Floodlighted section of a wall surrounding the Old City of Jerusalem, Israel, adjacent to the Jaffa Gate. Light sources are 400-W HPS units giving an average illuminance level of 50 lux. A sodium source was chosen to enhance the yellow-red color of the stone. (b) Church of All Nations, Mount of Olives, Jerusalem, Israel. Floodlight sources are 250- and 400-W mercury and metal–halide units, giving an average illuminance of 70 lux. Sources were selected to complement the colors in the mosaic at the top of the façade. (Photos courtesy of City of Jerusalem and J. Stroumsa, Chief Engineer.)*

such as air-traffic control rooms, continuous process manufacturing control areas, and the like.
- Installations where lamp heat is highly undesirable and its removal is difficult, expensive, or both. Among these are store show windows, refrigerated showcases, and conditions where lamp heat is felt by the space occupant(s), such as halogen and other incandescent lighting at workstations and low-ceiling spaces.

Fig. 17.29 *A "lollypop" fixture, even if aesthetically pleasing to some, gives poor illumination downward (note the large collar). This type of luminaire causes light pollution. (Photo by Nathan Majeski.)*

- Installations where the presence of electrical wiring is undesirable, such as patient-controlled hospital bed lighting or light sources in devices used by children.
- Spaces classified by the *National Electrical Code* (*NEC*) as electrically hazardous. These areas typically use large, heavy, expensive, and inefficient explosion-proof lighting.
- Installations where the electric and magnetic fields produced by fluorescent and HID lighting fixtures are unacceptable.
- Applications where the light source must be very small and effectively invisible.

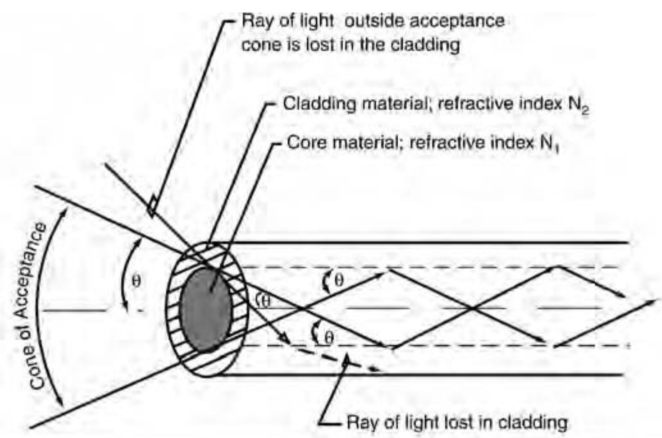
Two basic designs have been developed over the years to fill these lighting requirements: arrangements using optical fibers, and those using light guides of various types. Applications of these two techniques do not generally overlap, and they are therefore discussed separately in the following sections.

17.36 FIBER-OPTIC LIGHTING

Fiber optics have been in use for years, principally in instruments designed to permit illumination and observation of essentially inaccessible locations. In medical instruments designed for intrusive applications, fiber-optic (FO) cable has the additional advantages of absence of heat and elimination of electrical wiring, both of which could be at the very least uncomfortable and frequently dangerous when inserted into the body.

The physical principle by which an optical fiber conducts light is that of total internal reflection, illustrated in Fig. 17.30. The fiber is constructed of an inner core of transparent material (silica, glass, optical plastics) and an outer coating (cladding) of another material of *lower* refractive index. Because of this difference in refractive indices, light rays within the acceptance cone angle (2θ) are reflected at the interface of the two materials and thus proceed almost unimpeded down the core by a series of 100% reflections. Although there is (theoretically) no loss at the reflection, the core material itself exhibits an optical impedance that varies with the type of material. Ultraclear glass fibers, used in communications, have losses as low as 1 dB per kilometer, whereas the best plastic optical fiber used today has losses in the area of ⅓ dB per *meter*—that is, several hundred times as high. However, because of the short distances involved, these plastic fibers are satisfactory for lighting work (1-dB loss is the equivalent of 8.6% loss per meter, or 2.6% loss per foot).

Air, with a refractive index of 1.0, can also be used as a "cladding" material (unclad core), resulting in a fiber that emits light over its entire length. This light is shown in Fig. 17.30 as light "lost" in the cladding. In practice, a bare core is not used because it would be damaged at supports, and dirt accumulation on the surface would result in high losses. Side-light fibers (lateral mode) are constructed commercially of a core, cladding, and sheathing, all of which are transparent plastic materials with decreasing refractive index from core to sheath. Note also in the figure that the angle θ, and therefore the size of the acceptance cone, increases with the difference in the refractive indices between cone and cladding. It is desirable to have an acceptance cone as large as possible (high numerical aperture) so that maximum light from the source (illuminator) can be introduced (coupled) into the fiber. Glass fibers are generally not used in lighting applications because of their high cost, small light-carrying capacity, and large bending radius. Table 17.5 shows the construction and major characteristics of typical lighting-use optical-fiber cables.



Core Index N_1	Cladding Index N_2	NA*	Cone Half Angle θ	Acceptance Cone (2θ)
1.4	1.3	0.52	31°	62°
1.4	1.0	0.98	78.5°	157°

*NA (Numerical Aperture) = $\sqrt{N_1^2 - N_2^2} = \sin\theta$

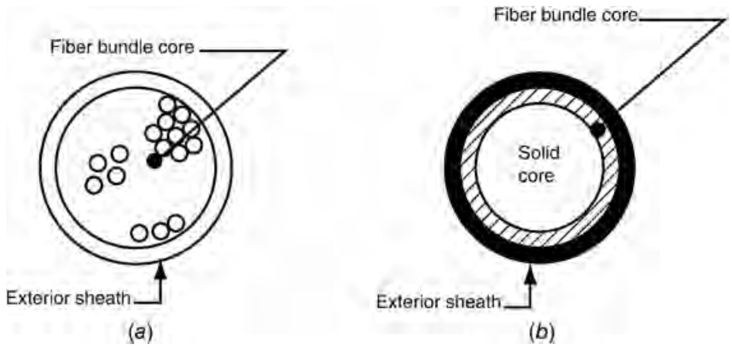
Fig. 17.30 *Schematic representation of the phenomenon of total internal reflection (TIR) in optical fibers (OF). Light rays entering the end of an OF at an angle to the fiber centerline no greater than θ are totally reflected at the interface between core and cladding. Angle θ is determined by the difference between the refractive indices of the core and cladding materials and increases as that difference increases. Light rays entering within the acceptance core (solid angle 2θ) travel along the fiber; all other light rays are lost.*

TABLE 17.5 Typical Characteristics of Plastic Optical-Fiber Cables

Type	Construction	*Diameter* Fiber/Core (mm)	OD (mm)	NA[a]	Cone Angle (degrees)	Attenuation Percent per Meter
End-light Fiber bundle	See Illustration (*a*)	0.15–2.0	6–18	0.5	60	4.7
Side-light Fiber bundle		0.15–2.0	6–14	0.5	60	4.7
End-light Solid core	See Illustration (*b*)	3–13	5–16	0.62	76	8.2
Side-light Solid core		7–13	9–16	0.57	70	23.7

[a]NA (Numerical Aperture) = $\sqrt{N_1^2 - N_2^2}$ = sin Θ; see Fig. 17.30.

Note: Sheathing is opaque for end-light cables and transparent for side-light cables.



17.37 FIBER-OPTIC TERMINOLOGY

Because FO cable is becoming common in lighting work, a lighting designer should be familiar with FO terminology. A brief glossary of the most important terms follows.

Acceptance angle (also acceptance cone). The maximum solid interior angle of a cone that defines the spread of light rays that will enter a single fiber. Because this angle is determined only by the fiber and the cladding materials, it is also the cone of light ray acceptance of a fiber bundle.

Attenuation. The degree of light reduction as it travels along the fiber. Because attenuation varies with frequency, the light color exiting an optical fiber is different from that entering, and the change becomes more pronounced with increasing fiber length.

Axial mode (also end-light). The mode of conduction from one end of the fiber (cable) to the other, with no deliberate loss by emission over the cable length.

Core. The center of an optical fiber that carries the light.

Fiber-optic port. A factory- or field-applied terminating connector that enables coupling of an FO cable to a light source or other item in the system. Glass FO is factory terminated; plastic fibers can be either.

Glass optical fiber. The type always used in communication work and seldom in lighting application. It is expensive, requires a large bending radius, and exhibits very low attenuation.

Illuminator. The light source in an FO lighting installation. It usually consists of a metal box containing the light source (usually metal–halide or halogen) and its accessories, plus required optical devices that collect and concentrate the light from the source and couple it optically to an optical port to which an optical cable is connected. The illuminator may also contain color filters, local and remote-control connections, and, almost always, a fan or blower for forced-air cooling of the source lamp.

Lateral mode (also side-light[ing]). A light conduction and distribution system whereby light is emitted over the entire length of the fiber, simulating neon tubing. This is accomplished by using transparent cladding and sheathing, with refractive indices selected to increase light rays entering (and leaving) the cladding.

Numerical aperture. A numerical metric based on the refractive indices of the core and cladding materials, indicating the angle of the acceptance cone (i.e., that portion of the light that is conducted by the fiber core).

Plastic optic fiber. The fiber material normally used in lighting work, usually a clear acrylic-type compound as the core, with various plastic compounds as cladding or sheathing, depending on the design and mode of operation. The fibers are classified by size as small core (up to 2 mm [0.08 in.] in diameter) and large core (up to 20 mm [0.78 in.] in diameter). Small-core fibers are manufactured in continuous and essentially unlimited lengths. Large-core fibers and sheathed fiber-bundle cables do not usually exceed 45 m (150 ft) in length.

Refractive index. The ability of a light-conducting (nonopaque) material to bend a light ray entering from another medium, expressed numerically.

Tail. A single optical fiber or a bundle of fibers extending from an illuminator to an output point. A single fiber separated from a bundle for a specific small, isolated illumination purpose (often decorative) is also referred to as a tail.

17.38 FIBER-OPTIC LIGHTING—ARRANGEMENTS AND APPLICATIONS

The development of large, efficient plastic optical fibers coupled with a concomitant price reduction has produced a lighting tool whose applications are limited only by the imagination of designers and manufacturers. In one form or another, optical fibers are applicable where:

- A single remote source can supply a large number of relatively small point-source lights.
- Burial of the light carrier (fiber bundle) in almost any substrate is desired or required.
- The heat, UV content, and electrical fields associated with most sources are absent.
- The presence of electrical wiring and its associated hazards are undesirable or unacceptable.

A few of the many current configurations are described in the following subsections.

(a) Axial-Mode Linear Devices

In this arrangement, a bundle of fibers is placed in a longitudinal enclosure, and individual fibers or small groups of fibers are separated from the bundle(s) and brought out of the enclosure as a light-emitting point (Fig. 17.31*a*). Most of these *light bars* are custom-made for a specific application, enabling the designer to specify all of the parameters, including spacing of points, intensity of each point, dimensions of the bar, individual fiber size and bundle size, color characteristics, and so on. Light bars are used in retail display lighting, accent lighting, directional devices, decorative applications, and other applications requiring a low-intensity, linear, and/or "sparkling" lighting device.

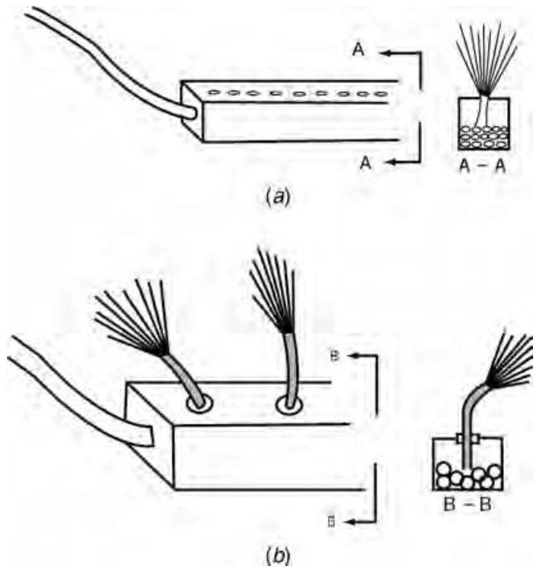


Fig. 17.31 *Linear constructions using end-light fibers. (a) A light bar is simply a box containing multiple tails that are brought out of the box-type container at intervals, usually equal. Selecting fiber size, exit spacing, and illuminator size creates a low-intensity linear lighting fixture. (b) By using large fibers and/or bundles brought out in adjustable groups, the designer can readily construct a linear bar with adjustable multihead spotlights.*

The essential design of a light bar can be adapted to the use of large-core fibers or multiple fiber bundles to produce a linear string of focusable, medium-intensity spotlights (Fig. 17.31*b*). In lieu of the closely spaced tiny light points of Fig. 17.31*a*, large fibers or bundles can be extracted. They can be used as light sources or can be coupled to optical plastic-fiber rods or other devices. These can then be "aimed" as desired to illuminate individual areas in a cabinet, store window, and the like. Here, too, the units are commonly custom-designed to perform a specific lighting task.

(b) Axial-Mode Discrete Sources

By using large groups of end-light FO bundles combined to produce a point light source, the designer can construct semiconventional lighting fixtures with a variety of common diffusing elements (Fig. 17.32). The advantages of these discrete sources compared to common electrically powered lighting fixtures are the same as those listed previously: absence of heat and electricity, and low maintenance and higher efficacy of high-output lamps in the illuminators. One disadvantage common to all plastic-fiber FO lighting is the necessity of keeping runs short due to the attenuation of the fibers. Lengths in excess of 20 ft (6.1 m) are inefficient and therefore uncommon.

(c) Lateral-Mode Fiber-Optic Lighting

As explained previously, lateral-mode fibers emit light throughout their length. This makes them particularly suitable for linear lighting tasks such as illuminating stair nosings, path lighting, and all sorts of decorative trim lighting. Figure 17.33 shows a possible arrangement for under-shelf lighting, illumination under stair nosings, and the like. The practicability of burying parts of the cable in concrete is useful in giving the remaining lighted cable a disconnected, floating appearance. Color filters in the illuminator, when applied to multiple cable runs as in Fig. 17.33, can produce dramatic outlining effects.

17.39 HOLLOW LIGHT GUIDES

The idea of conducting light from one place to another apparently arose several millennia ago from an architectural desire to provide daylight deep in interior spaces. The interior court is one example of an architectural light guide that is only recognizable as such in multistory buildings. Figure 17.34 illustrates the use of an interior light shaft in a six-story building. Notice the rapid attenuation as daylight descends by multiple reflections, accounting for the increasing size of the windows at lower levels. Indeed, attenuation is the principal problem with light pipes and guides that depend upon multiple internal reflections to conduct light any appreciable distance. The best metallic mirrors available today specularly reflect only about 95% of the impinging light. It is therefore relatively easy to calculate the number of 5% loss reflections that reduce

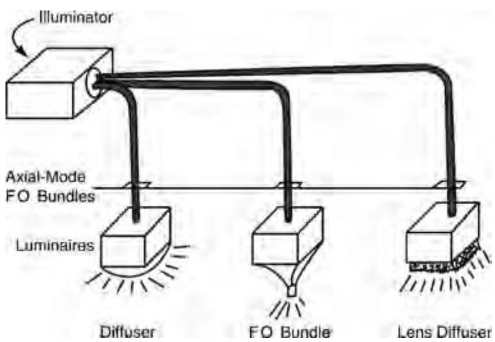


Fig. 17.32 *Relatively large end-light FO bundles can be utilized as point sources in conventional types of lighting fixtures.*

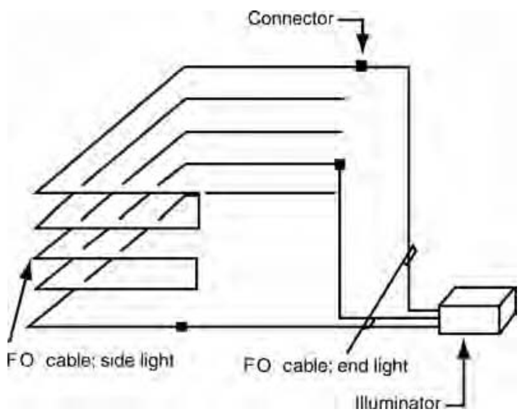


Fig. 17.33 *Side-light-emitting FO cables are ideal for linear lighting tasks such as stair-edge illumination, under-shelf lighting, and outline lighting of all sorts. The illustrated 3-tail arrangement is representative of this type of FO lighting.*

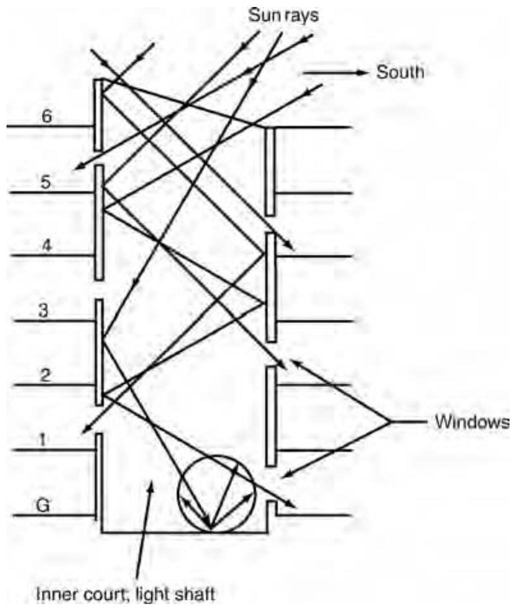


Fig. 17.34 *An interior court or light well (shaft) with a reflective wall surface acts as a light guide to introduce daylight at lower floors. Buildings in the northern hemisphere are oriented as shown. Due to attenuation of re-reflected sunlight beams traveling down the shaft, lower-floor windows are larger than those at upper floors to capture more (of the attenuated) light. (Reprinted from NASA Tech Brief LAR-12333.)*

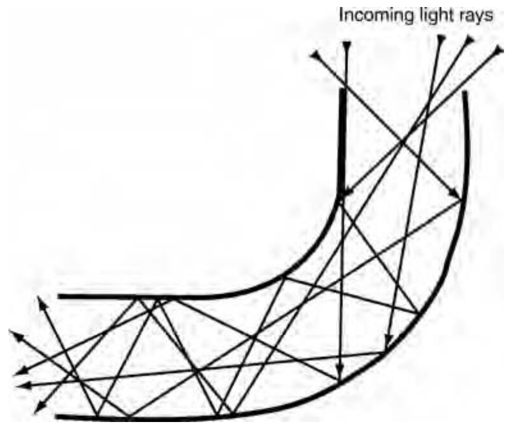


Fig. 17.35 *Curvature in a light guide increases the number of reflections that a light ray makes over the guide length, thereby increasing attenuation. (Reprinted from NASA Tech Brief LAR-12333.)*

the output light from a light pipe with random nondirectional input to an uneconomical level (where the “free” light received is more expensive due to construction and maintenance costs than alternative electric light). Furthermore, open-ended light pipes of this sort (Fig. 17.35) are notoriously difficult to keep clean of dust and surface-reflectance degeneration, so that the 95% initial specular reflectance rapidly decreases to 85% semidiffuse reflection, thereby increasing ray re-reflection and consequently overall light attenuation. (Sealing the upper end of the pipe with a transparent medium is not advisable due to the rapid accumulation of dust and condensation.) In order to capture an appreciable amount of sunlight (sky light is insufficient), an open-ended pipe at roof level must be very large. This, in turn, increases construction and maintenance costs and decreases (in the case of a commercial building) the usable/rental area, making the light-guide idea generally impractical except for very short guides. Such commercially available units are essentially small skylights with an elongated, reflective collar.

One solution to the problem of rapid attenuation in a light guide caused by multiple interior wall reflections is to collimate the incoming light. This has the additional advantage of permitting reduction of the light guide’s cross-sectional area. Such a system, however, requires a sun-tracking arrangement, plus mirrors and lenses in a collimating optical train. A typical arrangement is shown schematically in Fig. 17.36. The increased efficiency of arrangements of this sort is often offset by losses in the optical train and increased equipment cost (although the light pipe itself is smaller and therefore cheaper). Systems of this type are in use today, with generally satisfactory results, although system economics is marginal except in arid, sunny climates.

17.40 PRISMATIC LIGHT GUIDES

The first major improvement in hollow light guide design occurred in 1981, with the development and patenting of a prismatic rectangular hollow acrylic light guide (Whitehead, 1982). The patentable novelty of this device is that the facets of the prismatic exterior transparent acrylic walls of the pipe act as total internal reflection “mirrors,” thus preventing light from escaping from the transparent box guide. As a result, light is guided along the length of the device with very low losses, because

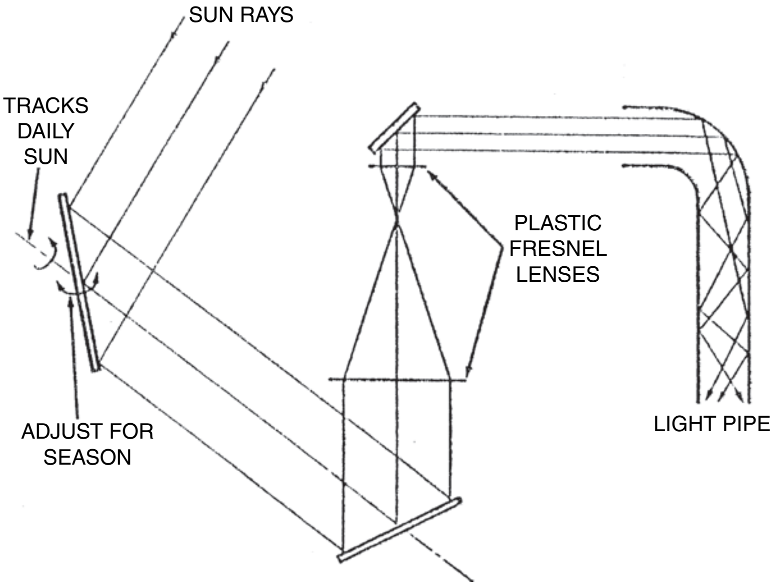


Fig. 17.36 *Concentration and collimation of sunlight can be accomplished with a sun-tracking mirror and an optical train of mirrors and lenses. Full tracking of the sun requires altitude and azimuth drives on the collection mirror. To reduce costs without severely reducing collection efficiency, a full azimuth drive tracks the sun from east to west daily, while the mirror tilt around a horizontal axis (altitude tracking) is adjusted only seasonally to the mid-season position. (The sun's maximum altitude varies 23.5° from equinox to solstice.) (Reprinted from NASA Tech Brief LAR-12333.)*

reflection at the prismatic walls is theoretically perfect, and losses in the air space within the guide are very small. In practice, it was found that at each reflection about 2% of the light was lost by absorption and, because of microscopic imperfections in the prisms, about 6% escaped through the wall. This 6% "loss" converts the light guide into a long, rectangular lighting fixture emitting light *uniformly* over its entire length. Placing a mirror at the end of the guide causes all the light reaching the end to be reflected back into the guide, thereby increasing the light output over its length. Overall efficiency of this extended "lighting fixture" is high; this fact, combined with very low maintenance, produced a highly desirable lighting product. Its first application was in an electrically hazardous area previously illuminated by explosion-proof lighting fixtures (Fig. 17.37).

17.41 PRISMATIC FILM LIGHT GUIDE

In 1988, the 3M Company developed a thin plastic prismatic film that utilizes the principle of total internal reflection at the prism face. Tests have shown that this material loses only about 1% of the light at each reflection. As a result, tubular hollow light guides using this material can extend for several hundred feet if the input light is collimated (Figs. 17.38 and 17.39). When used as an extended lighting fixture, this light guide exhibits good photometric characteristics.

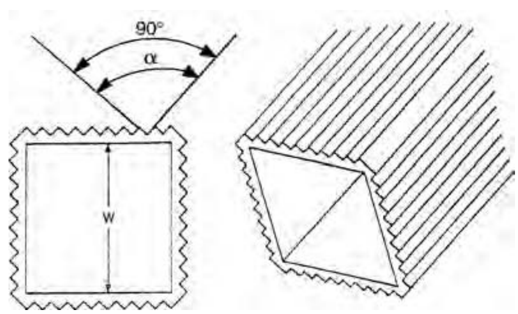


Fig. 17.37 *Views of the hollow, clear acrylic, prismatic light guide developed by L. A. Whitehead. The cross section measures 13-cm (≈5 in.) square, and the prism angle α is 90°. (Reprinted from Whitehead, 1982.)*

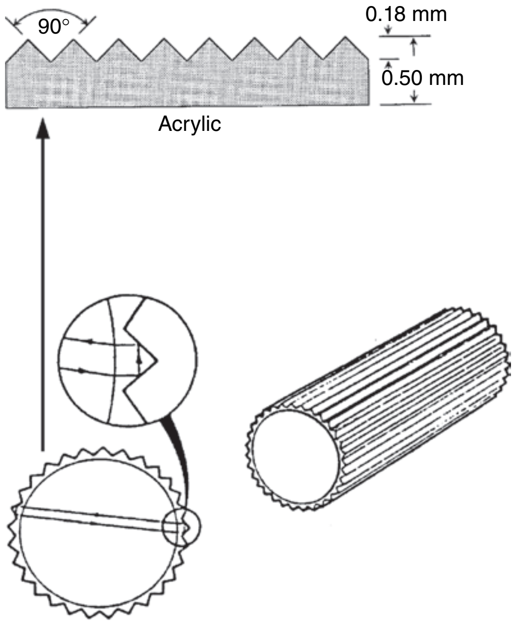


Fig. 17.38 Circular hollow light guide. If the prismatic plastic film is formed into a cylindrical shape as shown, it will act as a light guide with very low losses (0.18 mm = 0.007 in.; 0.5 mm = 0.02 in.). (Reprinted from a paper presented at Globalcon '96 by K. G. Kniepp of the 3M Company.)

Prismatic light pipes have all the advantages of FO lighting but fewer limitations, although in practice the two systems do not compete because they address entirely different needs. In addition to having all the advantages of remote-source FO lighting—including absence of heat, minimum UV radiation, absence of electrical wiring and the associated electromagnetic fields and electrical wiring hazards, and usability at any temperature, interior or exterior—prismatic light guides (and lighting fixtures) are constructed to handle very large quantities of light and do not produce color distortion (as do optical fibers). As a result, a luminous light pipe (light fixture) can be coupled to a very-high-output source such as an arc lamp, xenon lamp, or the relatively new sulfur lamp, and the pipe can be used to illuminate large areas, either interior and exterior. The economies in wiring, luminaires, installation, and maintenance help to offset the cost of the prismatic material.

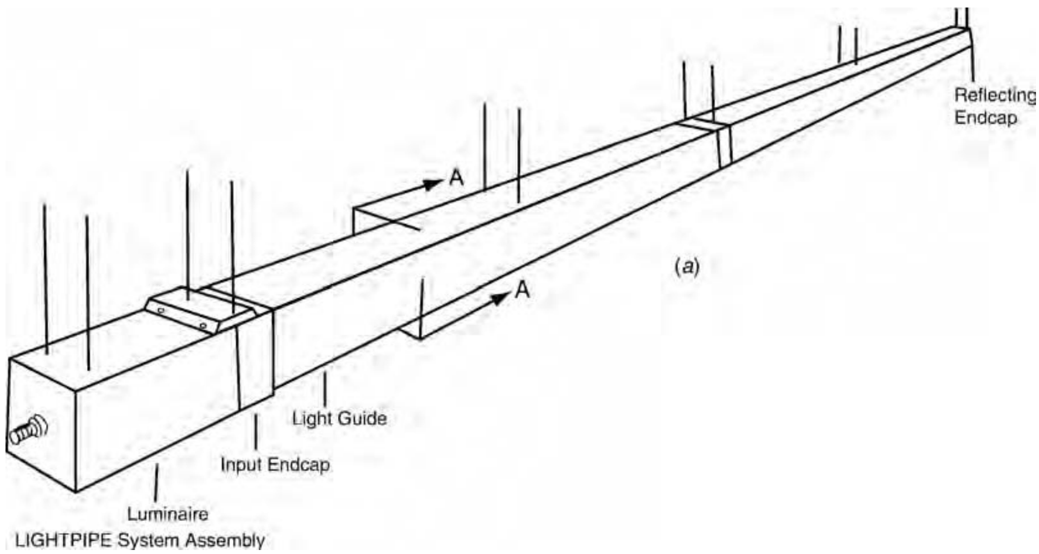
Because of the very high light conduction efficiency of optical lighting film (OLF), using it as a lighting fixture requires special techniques and materials to extract light from the pipe. One method is to apply another prismatic material to the inside of the light pipe with a different prism angle that causes incident light to change direction and exit the pipe. When this material is placed judiciously, selected areas of the pipe circumference emit light, in effect producing a longitudinal lighting fixture with the desired directionality. Typical lighting applications of prismatic film light-pipe fixtures are high-bay industrial and commercial installations, large exterior signs, tunnel illumination, highway signs, continuous rail-type guidance illumination, and exterior architectural building lighting. Figure 17.40 shows a circular prismatic light guide designed for exterior use, with several configurations and the associated photometric data. Figure 17.41 shows an application of the prismatic light-guide fixture.

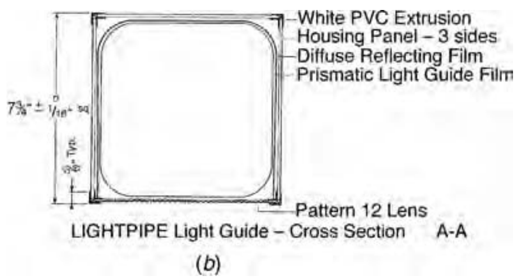
17.42 REMOTE-SOURCE STANDARDS AND NOMENCLATURE

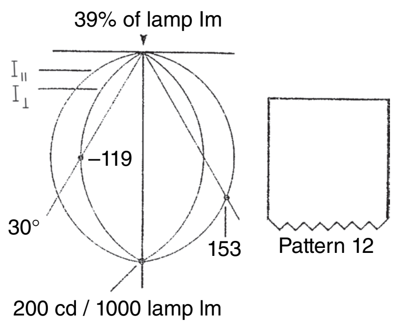
Due to the relative newness of long, remote-source tubular lighting, industry-wide standards for said lighting do not exist, and even nomenclature varies. Clear differentiation between devices intended primarily to carry light from one location to another and devices intended to illuminate along their length does not exist. Nor is terminology differentiated between light guides operating on the principle of internal reflection from specular surfaces and prismatic light guides. All these devices are variously and interchangeably referred to as:

- Hollow light guide
- Light pipe
- Hollow light pipe
- Prismatic light guide
- Prismatic light pipe
- Hollow prismatic light guide
- Remote-source hollow light guide

and various other names. See NEMA LSD 4-1999, *Glossary of Terms Pertaining to Remote Illumination Systems* for further information.





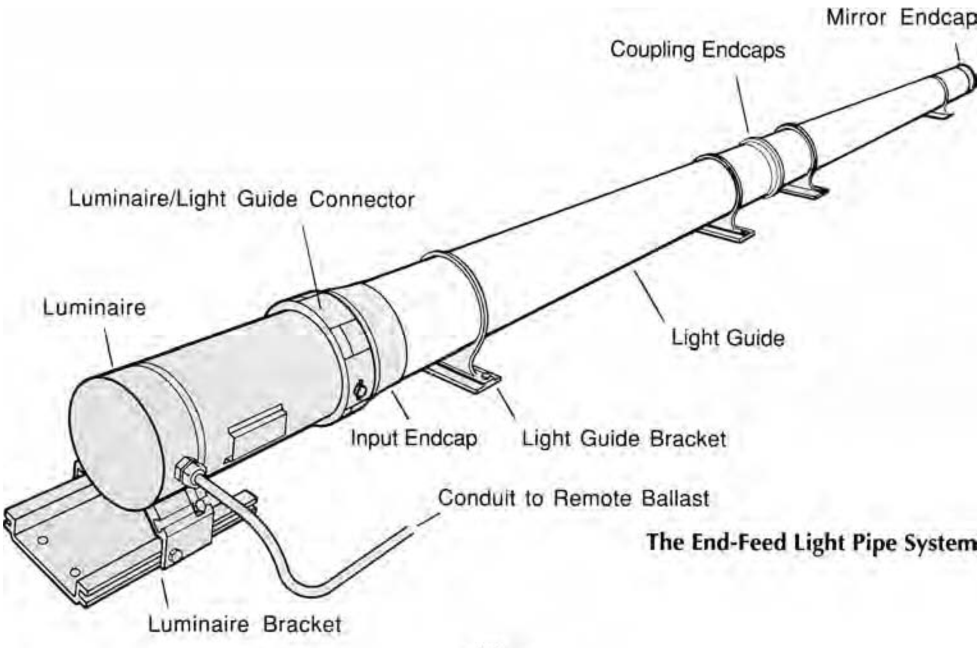


Pcc	80		50		30	
Pw	50	30	50	30	50	30
RCR						
0	.46	.46	.43	.43	.41	.41
1	.41	.40	.39	..38	.37	.37
2	.37	.35	.35	.33	.34	.32
3	.33	.31	.32	.30	.31	.29
4	.30	.27	.29	.26	.28	.26
5	.27	.24	.26	.23	.25	.23
6	.25	.22	.24	.21	.23	.21
7	.22	.19	.21	.19	.21	.19
8	.20	.17	.19	.17	.19	.17
9	.18	.15	.18	.15	.17	.15
10	.17	.14	.16	.14	.16	.13

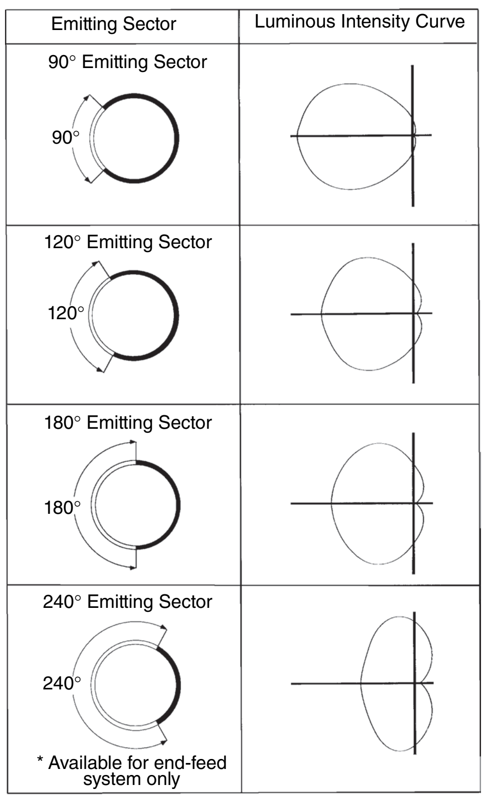
CU Table – One Side Emitting

(c)

Fig. 17.39 *Details of a rectangular light-guide fixture. (a) The entire lighting unit comprises a "luminaire" at one end containing the light source (250- or 400-W metal–halide lamp) and its accessories connected to the hollow prismatic light guide. The end of the guide is sealed with a mirror that reflects the light back into the light guide. (b) The light guide itself is enclosed on three sides and equipped with a prismatic lens diffuser on the open (bottom) surface through which light is emitted. This specific design is usable to a length of 40 ft (12 m). Longer units are equipped with light sources at both ends. (c) Photometric characteristics of the luminaire-light guide assembly. (Courtesy of TIR Systems, LTD.)*



(*a*)



(*b*)

Fig. 17.40 *Details of a 7-in. (178-mm) diameter hollow prismatic end-feed light-guide fixture. (a) The entire unit consists of an opaque "luminaire" section containing a 250-W metal–halide lamp connected to a 7-in. (178-mm) diameter acrylic tube up to 44 ft (13 m) in length containing prismatic optical film and terminating in a reflective (mirrored) endcap. (b) The portion of the tube circumference that emits light (uniformly) is controlled by placement of a diffuse reflecting film between the inner prismatic film and the outer transparent acrylic envelope (see Fig. 17.39*b*). The reflective film is shown as the black portion of the tube circumference. (c) Photometric data for an end-feed system with a single 250-W metal–halide source. (Courtesy of TIR Systems, Ltd.)*

Cu Tables — End-Feed System

ρ_{cc}	70		50	
ρ_w	50	30	50	30
RCR				
0	.34	.34	.32	.32
1	.30	.29	.29	.28
2	.26	.25	.25	.24
3	.24	.21	.23	.21
4	.21	.19	.20	.18
5	.19	.16	.18	.16
6	.17	.14	.16	.14
7	.15	.13	.15	.12

CU Table - 90° Emitting

ρ_{cc}	70		50	
ρ_w	50	30	50	30
RCR				
0	.36	.36	.34	.34
1	.30	.29	.28	.27
2	.26	.24	.24	.23
3	.23	.20	.21	.19
4	.20	.17	.19	.16
5	.17	.15	.17	.14
6	.15	.13	.15	.12
7	.14	.11	.13	.11

Cu Table - 120° Emitting

ρ_{cc}	70		50	
ρ_w	50	30	50	30
RCR				
0	.39	.39	.36	.36
1	.33	.31	.30	.29
2	.28	.25	.26	.24
3	.24	.22	.23	.20
4	.21	.18	.20	.17
5	.19	.16	.18	.15
6	.17	.14	.16	.13
7	.15	.12	.14	.11

CU Table - 180° Emitting

ρ_{cc}	70			50	
ρ_w	50	30		50	30
RCR					
0	.39	.39	.39	.35	.35
1	.32	.30	.28	.29	.27
2	.27	.24	.22	.24	.12
3	.23	.20	.18	.21	.18
4	.20	.17	.15	.18	.16
5	.18	.14	.12	.16	.13
6	.16	.13	.10	.14	.11
7	.14	.11	.09	.13	.10

Cu Table - 240° Emitting

Length of Run (feet)		10 ft.	20 ft.	30 ft.	40 ft.
Lumens/foot		500 lm/ft.	270 lm/ft.	165 lm/ft.	110lm/ft.
Peak Luminous Intensity (cd)\(Mean Exitance (lm/ft^2))	90° emitting	1569\(1070)	1708\(583)	1569\(357)	1435\(245)
	120° emit	1143\(850)	1243\(462)	1143\(283)	1043\(194)
	180° emit	1091\(631)	1187\(343)	1091\(210)	998\(144)
	240° emit	696\(497)	757\(270)	696\(166)	N/A

Note: All values listed are based on the maintained output of a single T250 luminaire.

Photometric Data - End-Feed System

(*c*)

Fig. 17.40 *(Continued)*

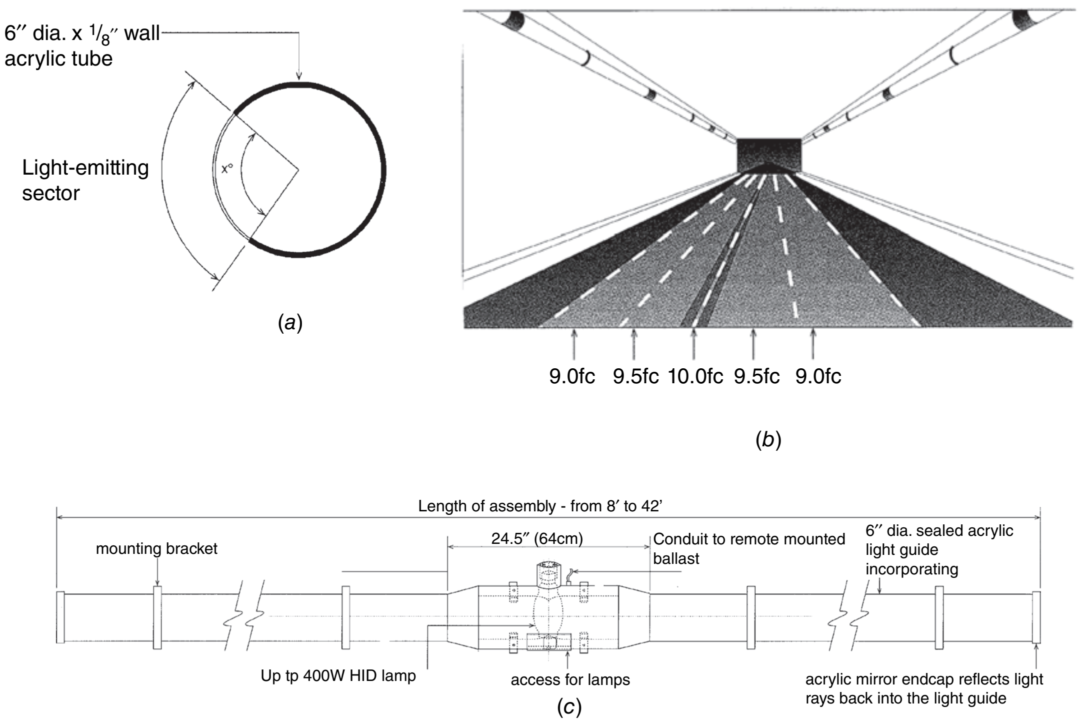


Fig. 17.41 *Application of a prismatic tubular light guide to tunnel lighting. (a) Section demonstrating how light is emitted from the light guide. (b) Perspective drawing showing tubular lighting on both sides of the tunnel and the resultant uniform tunnel illuminance levels. (c) Drawing of one section of the center-feed light guide. (Courtesy of TIR Systems, Ltd.)*

References and Resources

ASHRAE. 2013. ANSI/ASHRAE/IESNA Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

ASHRAE. 2010. ANSI/ASHRAE Standard 90.2-2010, *Energy-Efficient Design of Low-Rise Residential Buildings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

IEEE. 1995. Standard 446, *IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications*. Institute of Electrical and Electronics Engineers, Inc. New York, NY.

IESNA. 2011. *The Lighting Handbook,* 10th ed. Illuminating Engineering Society of North America. New York, NY.

IESNA. 2011. TM-10-00: *Addressing Obtrusive Light (Urban Sky Glow and Light Trespass) in Conjunction with Roadway Lighting*. Illuminating Engineering Society of North America. New York, NY.

IESNA. 2011. TM-11-00: *Technical Memorandum on Light Trespass: Research, Results, and Recommendations*. Illuminating Engineering Society of North America. New York, NY.

IESNA. 2012. RP-1-12: *American National Standard Practice for Office Lighting*. Illuminating Engineering Society of North America. New York, NY.

IESNA. 2013. RP-3-13: *American National Standard Practice on Lighting for Educational Facilities*. Illuminating Engineering Society of North America. New York, NY.

International Dark-Sky Association (light pollution): www.darksky.org/

NASA. NASA Tech Brief. PB80-974440 (LAR-12333): *Optics for Natural Lighting*. National Aeronautics and Space Administration, Langley Research Center. Hampton, VA.

NEMA. 1999. LSD-4-1999, *Glossary of Terms Pertaining To Remote Illumination Systems.*

National Electrical Manufacturers Association. Rosslyn, VA.

NFPA. 2012. NFPA-101: *Life Safety Code*. National Fire Protection Association. Quincy, MA.

NFPA. 2014. NFPA-70: *National Electrical Code*. National Fire Protection Association. Quincy, MA.

NFPA. 2012. NFPA-99: *Health Care Facilities Code*. National Fire Protection Association. Quincy, MA.

Whitehead, L. A., R. A. Nodwell, and F. L. Curzon. 1982. “New Efficient Light Guide for Interior Illumination.” *Applied Optics*, Vol. 21, Issue 15, pp. 2755-2757.

CHAPTER 18

Water and Basic Design

"THE NEXT GREAT WORLD CRISIS WILL BE water supply." This prediction is becoming increasingly pertinent in the modern day, as many scales of conflict over water rights are coming to the forefront—downstream nation-states vocalizing threats of aggression against their upstream neighbors, municipalities engaging in legal battles over aquifer claims, and so on.

With a finite planetary water supply, pitted against an increasing population, seen in conjunction with an increasing *per capita* consumption of water, we see again (as with fossil fuels) the problem of limited resources met with growing demand. At least in this case, the amount of water is fixed, not diminishing. However, the problem of fair allocation remains (Fig. 18.1). Countries have fought wars over oil; must they also wage war over water?

Agricultural and industrial use of water may dwarf that of buildings, but designers still have a role in this dilemma. We can use water both efficiently and aesthetically where it is appropriate, and avoid its use when possible.

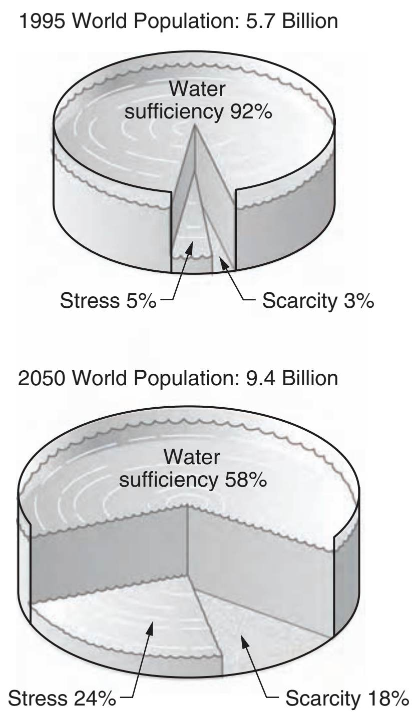


Fig. 18.1 *Earth's present and projected future annual per capita fresh water supply for all purposes. The relative size of the graphs reflects population growth. A "sufficient" supply is 1700 m³ (449,000 gal) per person; the "stress" supply is between 1000 and 1700 m³ (264,180 and 449,000 gal) per person; the "scarcity" supply is less than 1000 m³ (264,180 gal) per person. Currently, worldwide water use is 70% irrigation, 20% commercial-industrial, and 10% residential. (Worldwatch,* State of the World 1999*; courtesy of Population Action International.)*

18.1 WATER IN ARCHITECTURE

Throughout history, in nearly all climates and cultures, the designer's major concern about water was how to keep it *out* of a building. Only since the end of the nineteenth century has a water supply *within* a building become commonplace in industrialized countries. In much of the world today, running water is still not available within most buildings. There are a variety of appropriate design responses to the supply, use, and return of this versatile commodity.

(a) Nourishment

Water is the most abundant chemical in our bodies as well as in our diet. From a larger perspective, though, the amount of pure (potable) water that we actually need for drinking and cooking is very small—only about 3 g/cd (gallons per capita per day) (11.4 L/cd) in the United States. The most common supply system throughout history has been the central municipal fountain or well (Fig. 18.2), whose technical importance to the community has often been emphasized by the aesthetics of both the fountain's overall sculptural composition and the elegance of detail in its water spouts, basins, and other elements. A fountain, centrally located within a municipality, serves not only as a geographic point from which the townspeople can access a vital resource, but also as a social hub wherein opportunities for conversations and interactions abound.

As potable water became available on demand within buildings, water-related social opportunities diminished. However, employees still converse around the drinking fountain—for example, when it is located in a place that invites lingering or relaxing.

Fig. 18.2 *The fountain in San Lorenzo, Italy, serves as a social space and place of coolth. (© Donald Corner; used with permission).*

(b) Cleansing and Hygiene

Water is a nearly ideal medium for the dissolution and transport of organic waste, and because of its high heat-storage capacity, it easily retains comfortable temperatures for bathing. Much larger quantities of water are used for cleaning than for nourishment: In the average U.S. home, about 14 g/cd (53 L/cd) are used for clothes washing and dishwashing, and another 21 g/cd (79.5 L/cd) are used for bathing and personal hygiene.

In the past, water for cleaning was carried to the home infrequently; the Saturday night (only) bath was typical well into the twentieth century in the United States. Bathing vessels were usually portable and sometimes were combined with other pieces of furniture (a couch that sat over a tub, a metal tub that folded up inside a tall wooden cabinet, etc.). Thus, a *bathplace* rather than a bathroom was the common design response.

Although the physical constraints of water carrying were important design influences on bathing, cultural attitudes were at least as strong an influence throughout history. Perhaps the most startling contrast was between the medieval concept of bathing as an almost sinful indulgence, and the earlier Roman attitude toward public baths as the social centers of cities.

Today bathing facilities are commonly designed to be used in a personal, private setting. There are also welcome opportunities to design more social bathing (recreational rather than cleansing) places, such as swimming pools, bathhouses, and hot tubs. The characteristics of the water supply (spouts, jets, cascades) can be matched with those of the water surface desired (mirror-smooth, gently flowing, rippled, rolling, foaming) in order to obtain the intended atmosphere.

(c) Ceremonial Uses

Water acquired a ceremonial significance that remains particularly evident in religious services. Examples of the ceremonial use of water include vessels containing holy water at entrances to Catholic churches, pools and fountains in the forecourts of mosques, full-immersion baptismal fonts at the altars of some Protestant churches, and the Jewish tradition of tashlich whereby some shuls employ a fountain or pool for the purpose. The opportunities for aesthetic expression are particularly rich in these ceremonial applications.

(d) Transportation Uses

In stark contrast to its uses in nourishing, cleansing, and celebrating, water is used in our buildings principally to transport organic waste. The typical U.S. home uses 32 g/cd (121 L/cd) just to flush toilets. There is perhaps no more flagrant example of a mismatch in architecture than the high-grade resource of pure water being used for the low-grade task of carrying away a cigarette butt.

In the past, table scraps were commonly fed to animals or composted, and human waste was thrown out of windows (accompanied by warning cries) or deposited in holes below outhouses. Organic waste disposal was thus dependent on either portable vessels or special structures set apart from the typical building.

As water supplies were developed, water's advantages over the foul smell and inconvenience of these methods became irresistible. A typical sequence of events unfolded on Manhattan Island. In the 1700s, Manhattan was farm country that, like all other areas that later developed into large cities, had minimal water needs. Potable water was available in shallow wells and from some springs and streams. These sources were largely unaffected by the minor ground pollution from widely separated dry-pit privies (outhouses) that received human wastes. Paved city streets appeared in the 1800s, at which time the natural streams were enclosed in pipes called *storm sewers*. These pipes led the rainfall to the many waterways surrounding the island. Then in the late 1800s, flush toilets appeared. It seemed natural to connect the toilets to the already established storm sewers and to rename the pipeways *combined sewers*, which now carried both storm water and so-called sanitary drainage to the rivers (sanitary for the building, but not for the rivers). Fast-flowing rivers were utilized as natural sewage treatment plants, and surprisingly, for many decades they did a fair job of keeping pollution reasonably in check. With the prospect of future sewage treatment plants, separate *sanitary sewers* were built. Also, there were some remaining (and some newly built) storm sewers that did not carry the wastes from toilets.

In cities where this confused pattern of sewer systems still exists (including most larger and older cities), it is now extremely difficult and expensive to sort out and reroute sewers so that *only* sanitary drainage goes to treatment plants and *all* storm drainage goes to waterways or into the ground. It seems particularly ironic that in most U.S. locations the rainwater that falls on a home's roof is adequate in both quality and quantity to supply a family's cleaning needs (21 + 14 = 35 g/cd) (132 L/cd). In this chapter and in Chapter 19, these possibilities for rainwater are developed further.

As the human waste disposal place became a room within a building, the design issues grew more complex. Physically, there was a need for running water and for large-diameter pipes that sloped downward continuously from the toilet to a sewer or septic tank. As sewer gas became a recognized problem, an elaborate system of traps and vents became necessary. Again, cultural attitudes were also influential: How private an activity was this elimination from the body? To what extent could/should one plumbing fixture accommodate both body cleansing and waste elimination? If males insisted on standing rather than sitting while urinating, how could one devise a toilet that would also properly accommodate defecation, which requires a low seat?

(e) Cooling

Water has a remarkable cooling potential: It stores heat readily, removes large quantities of heat when it evaporates, and vaporizes readily at temperatures commonly found at the surface of human skin. In hot-dry climates, designers can place water surfaces (or sprays) upwind from the place to be cooled or resort to the evaporative coolers. Cooling towers are familiar components of large-building cooling systems.

Because all of us have experienced the physical cooling of the skin by water, we all carry psychological associations between water and cooling that can enhance our comfort on hot days. The sight of sunlight reflected on a water surface, with its characteristic "dancing" quality, connotes coolness, as does the sound of running or splashing water. Thus, even when water does not physically cool people, it can make an important psychological contribution to human comfort (Fig. 18.3).

Fig. 18.3 *Water as an aesthetic feature of a courtyard during the hot-arid season in Colima, Mexico. The sound and sight of running water add to a psychological impression of coolness.*

(f) Ornamental Uses

In almost any landscaping application, indoors or out, water becomes a center of interest. Our association of water with nourishing, cleansing, and cooling makes water a very powerful design element—a fact recognized by landscape designers throughout history. In arid regions, water is often used sparingly, in small, tightly controlled channels and at lower flow rates. The gardens of Islamic architecture in the Middle East are especially effective demonstrations of such design restraint. Where water is more plentiful, it has been used lavishly, as at the Villa d'Este in Tivoli, outside Rome, where much of a river's flow is diverted through the gardens.

Especially useful design characteristics of water include: its *reflectivity*, which sets it apart from most plant and ground materials in a garden; its *liquidity*, which attracts attention to its motion and creates unique sounds wherever it is moved; and its *life-sustaining* potential, which allows the addition of both water plants and animals to a garden.

(g) Protective Uses

Every designer dreads water's ability to penetrate a roof and damage a building and its contents. However, we all depend on water as the best fire protection medium available in most buildings. The vast quantities of water potentially required for firefighting must be delivered quickly—resulting in the necessity of large-diameter pipes regulated by very large valves. Because this system's distribution tree must be immediately obvious to firefighters, some degree of exposure is prudent. Despite its size and guarantee of at least partial exposure in public places, a fire protection water supply system is rarely treated as a visually integral design element. This mismatch of potential and actuality is discussed further in Chapter 25.

Another protective use of water has been as a means to control circulation; moats around castles may seem quaint today, but designers still sometimes use water as a means of directing traffic over a bridge to an entry.

18.2 THE HYDROLOGIC CYCLE

There is a finite quantity of water in the Earth and its atmosphere. The process whereby this water constantly circulates, powered by about one-fourth of the Earth's solar energy, is called the *hydrologic cycle* (Fig. 18.4). More than 99% of this water is "inaccessible"—either because it is saltwater, or because it is frozen in glaciers and polar ice caps. The most accessible sources of water are precipitation and runoff.

Precipitation has the advantage of relative purity, although acid rain is a growing threat in many parts of the world, including much of the United States and Canada. Like solar energy, precipitation is a very large but very thinly spread resource; its capture is therefore likely to take place on an individual basis. It is predictable that until we experience a water crisis similar to the energy crisis that began in the 1970s, rainwater capture will remain a mostly untapped resource in the United States.

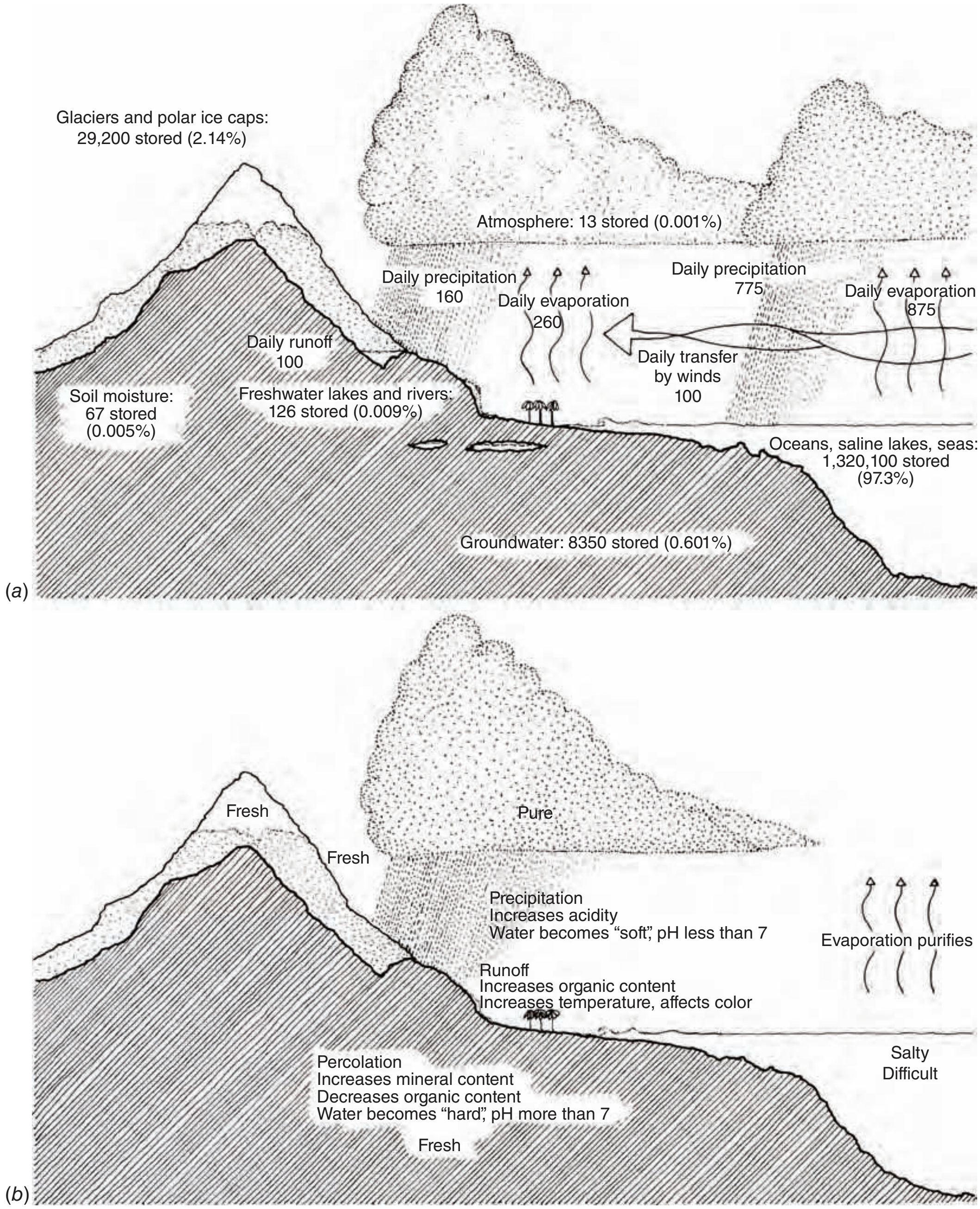


Fig. 18.4 *(a) Hydrologic cycle. The figures given are in cubic kilometers. "Evaporation" includes transpiration from plants as well as evaporation from surfaces. "Precipitation" can be rain, hail, sleet, or snow. The vast majority of stored water is in the ocean. (b) Quality of water at various stages within this cycle.*

Runoff enjoys the advantage of a concentrated flow of water, which permits easy capture of large quantities. Its most serious disadvantage is the possibility of pollution—organic, chemical, and radioactive—depending on what is upstream from the point of capture. In some regions of North America, river water is reused 50 times on its way to the ocean. Further discussion of water sources and treatments occurs in Chapters 19 and 20.

That part of daily precipitation that neither evaporates nor joins the runoff becomes part of *soil moisture*. Much soil moisture is used by growing plants and is quickly transpired (evaporated) by the plant into the atmosphere. The remaining water works downward below the root zone of plants, eventually reaching a zone of saturation, where all voids in the ground are filled with water. This zone of saturation is called *groundwater*; the upper surface of groundwater is called the *water table*. Wells are commonly sunk to a point well below the water table so that the latter's seasonal fluctuations will not interrupt the well's access to groundwater.

18.3 BASIC PLANNING

After considering the relationship between a building and the roles that water plays within it, the designer must do basic sizing of the quantities of water needed, of the areas in which water will be used, and of the areas and equipment associated with water's return to the hydrologic cycle.

However, before discussing basic planning for the amounts of water used daily within buildings, and for the treatment of that water, we should note that water is also an important component of building construction. The production of 1 ton (907 kg) of bricks requires 580 gal (2200 L) of water; 1 ton of steel requires 43,600 gal (165,000 L); 1 ton of plastic requires 348,750 gal (1.32 million L). Water is one of the main ingredients of concrete; a typical 94-lb (42.6-kg) bag of cement requires about 6 gal (23 L) of water.

Another way in which buildings contribute to water consumption is through electricity consumption. Most power plants require very large quantities of water, which they quickly return to the hydrologic cycle warmer in temperature (and perhaps as vapor). A large nuclear power plant that utilizes a cooling tower can evaporate daily the approximate equivalent of transpiration from about 9 mi^2 (23 km^2) of forest.

(a) Water Supply

The task of estimating water needs is complicated by the conflict between *current practice* and *conservation*. Current practice tends toward the use of large amounts of water for very low-grade tasks. Conservation reserves high-quality water for high-grade tasks and emphasizes recycling as well as diminished overall usage of water.

Water supply is often first estimated in terms of gallons per capita per day (liters per capita per day). Table 18.1 shows some common terms used in measuring the water supply. Typical quantities are matched with nourishing, cleansing, and other usages in the United States in Table 18.2. To gain an

TABLE 18.1 Water Measurement Terms and Conversions

QUANTITY	
1 gal	= 8.33 lb
	= 231 in.^{3}
	= 0.134 ft^3
	= 3.785 L
1 liter	= .0263 gal
1 cubic foot	= 7.48 gal
	= 62.4 lb
	= 0.028 m^3
1 cubic meter	= 1000 L
	= 35.32 ft^3
1 ton	= 240 gal
1 acre	= 0.4 hectare
	= 40 km^2
1 acre-foot (a-f)	= 325,851 gal
	= 43,560 ft^3
	= 12 acre-inches (ac-in.)
1 million gallons	= 3.07 a-f
FLOW	
1 cfs	= 1.98 a-f/day
	= 0.028 m^3/s
1 a-f/year	= annual water supply for five people at 180 gal/cd
1000 gpm	= 2.23 cfs
	= 4.42 a-f/day
1 million gpd	= 694.4 gpm
	= 1.55 cfs
	= 1120 a-f/yr
LEAKS	
Slow drip	= 170 gpd
	= 62,050 gal/yr
⅛-in. (3.2-mm) diameter stream	= 3600 gpd
	= 4 a-f/yr
COST	
10¢ per 1000 gal	= 7.48¢ per 100 ft^3
	= $32.59 per a-f
10¢ per 100 ft^3	= $43.56 per a-f
	= $13.40 per 1000 gal
10¢ per ton	= $136 per a-f

Sources: Milne (1976) and Ferguson (1998).

TABLE 18.2 Planning Guide for Water Supply[a]

	Per Capita (as Listed) Daily Usage	
Building Usage	**Gallons**	**Liters**
Airports (per passenger)	3–5	11–19
Apartments, multiple-family (per resident)	60	227
Bath houses (per bather)	10	38
Camps		
Construction, semipermanent (per worker)	50	189
Day with no meals served (per camper)	15	57
Luxury (per camper)	100–150	378–568
Resorts, day and night, with limited plumbing (per camper)	50	189
Tourist, with central bath and toilet facilities (per person)	35	132
Cottages with seasonal occupancy (per resident)	50	189
Courts, tourist, with individual bath units (per person)	50	189
Clubs		
Country (per resident member)	100	378
Country (per nonresident member present)	25	95
Dwellings		
Boardinghouses (per boarder)	50	189
Additional kitchen requirements for nonresident boarders	10	38
Luxury (per person)	100–150	378–568
Multiple-family apartments (per resident)	40	151
Rooming houses (per resident)	60	227
Single family (per resident)	50–75	189–284
Estates (per resident)	100–150	378–568
Factories (per person per shift)	15–35	57–132
Highway rest area (per person)	5	19
Hotels with private baths (two persons per room)	60	227
Hotels without private baths (per person)	50	189
Institutions other than hospitals (per person)	75–125	284–473
Hospitals (per bed)	250–400	946–1514
Laundries, self-service (per washing)	50	189
Livestock (per animal)		
Cattle (drinking)	12	45
Dairy (drinking and servicing)	35	132
Goat (drinking)	2	8
Hog (drinking)	4	15
Horse (drinking)	12	45
Mule (drinking)	12	45
Sheep (drinking)	2	8
Steer (drinking)	12	45
Motels with bath, toilet, and kitchen facilities (per bed space)	50	189
With bed and toilet (per bed space)	40	151
Parks		
Overnight, with flush toilets (per camper)	25	95
Trailer, with individual bath units, no sewer connection (per trailer)	25	95
Trailer, with individual baths, connected to sewer (per person)	50	189
Picnic		
With bath houses, showers, and flush toilets (per picnicker)	20	76
With toilet facilities only (per picnicker)	10	38
Poultry		
Chickens (per 100)	5–10	19–38
Turkeys (per 100)	10–18	38–68
Restaurants with toilet facilities (per patron)	7–10	26–38
Without toilet facilities (per patron)	2.5–3	9–11
With bar/cocktail lounge (additional quantity per patron)	2	8
Schools		
Boarding (per pupil)	75–100	284–378
Day, with cafeteria, gymnasium, and showers (per pupil)	25	95
Day, with cafeteria but no gymnasiums or showers (per pupil)	20	76
Day, without cafeteria, gymnasiums, or showers (per pupil)	15	57
Service stations (per vehicle)	10	38
Stores (per toilet room)	400	1514
Swimming pools (per swimmer)	10	38
Theaters		
Drive-in (per car space)	5	19
Movie (per auditorium seat)	5	19
Workers		
Construction (per person per shift)	50	189
Day (school or office, per person per shift)	15	57

Source: U.S. Environmental Protection Agency (1975).

[a]These values may be reduced as follows: with flow controls, up to 25% reduction; with water recycling, up to 50% reduction.

appreciation of how the rate of urban water usage has changed over time, consider the following figures (from Milne, 1976):

Imperial Rome	38 g/cd (144 L/cd)
London, 1912	40 g/cd (151 L/cd)
American cities just before World War II	115 g/cd (435 L/cd)
Los Angeles, mid-1970s	182 g/cd (689 L/cd)

Compare these usage rates to the "Basic Water Requirement" for four domestic needs—drinking, sanitation, bathing, and cooking—of about 13 g/cd (50 L/cd) proposed by Gleick (1998).

Although the historical trend has clearly been toward higher per capita use of water, the recent emphasis on conservation has resulted in significant changes in this pattern. Table 18.2 can be used to estimate the daily indoor usage of water in various facilities if *current practices* are anticipated. For a very rough approximation of *conservation* effects:

- Reduce Table 18.2 values by 25%, assuming simple conservation measures such as flow controls.
- Reduce Table 18.2 values by 50%, assuming partial recycling.

The amount of water used for flushing toilets within the building types listed in Table 18.2 shows the great potential for savings through conservation.

In urban areas, public water mains usually provide the necessary quantities of water at the pressures and rates of flow required to operate typical plumbing fixtures. For isolated buildings or those independent of public networks, the water supply can come from individual sources: wells, springs, cisterns, lakes, and so forth. For the minimum pressures and flow rates necessary from these sources (and/or the storage vessels associated with them), see Table 19.14.

(b) Cisterns

Where rainwater is to be utilized, a rough approximation of catchment area and cistern storage volume is initially needed. This procedure is detailed later in this chapter. For now:

1. From Table 18.2, find the quantity of rainwater to be used daily:

$$\text{g/cd} \times \text{population} = \text{gpd}$$
$$(\text{L/cd} \times \text{population} = \text{L/d})$$

2. Convert this quantity to the yearly need for water:

$$\text{gpd} \times 365 \text{ days} = \text{gal/yr}$$
$$(\text{L/d} \times 365 \text{ days} = \text{L/yr})$$

3. Assume, conservatively, that a dry year will have two-thirds of the precipitation of an average year; this measurement is the *design precipitation*. (Average annual precipitation is available from National Oceanic and Atmospheric Administration [NOAA] annual summaries.)

$$\text{Average annual precipitation} \times \tfrac{2}{3} = \text{design precipitation}$$

4. From Fig. 18.5, determine the catchment area required.
5. Roughly size the cistern (storage) capacity by finding the longest dry period (in days of negligible rainfall, from NOAA local climatological data):

$$\text{cistern capacity} = \text{gpd} \times \text{days of dry period}$$

6. Convert capacity to volume by the formula

$$1 \text{ ft}^3 \text{ stores } 7.48 \text{ gal of water}$$
$$(1 \text{ m}^3 \text{ stores } 1000 \text{ L water})$$

EXAMPLE 18.1, PART A A 20,000-ft^2 (1860-m^2) one-story factory near Salem, Oregon, will use roof-collected rainwater to flush its toilets. Water-conserving 3 gal/flush (11.4 L/flush) toilets will serve 20 workers. Table 18.2 shows that factory workers use between 15 and 35 gal/cd (57–132 L/cd). Because usage at this factory will be low—no showers, for example—assume 15 gal/cd (57 L/cd):

$$15 \text{ gal/cd} \times 20 \text{ workers} = 300 \text{ gpd for } \textit{all} \text{ usages}$$
$$(57 \text{ L/c/d} \times 20 = 1140 \text{ L})$$

Because low-flush toilets are to be used, reduce this figure by 25%:

$$0.75 \times 300 = 225 \text{ gpd } (0.75 \times 1140 = 855 \text{ Lpd})$$

Toilets will probably account for most of this 225 gpd (855 Lpd): for example, at three flushes per day per worker,

$$3 \text{ flushes/day} \times 3 \text{ gal/flush} \times 20 \text{ workers} = 180 \text{ gpd}$$
$$(3 \times 11.4 \text{ L/flush} \times 20 = 684 \text{ Lpd})$$

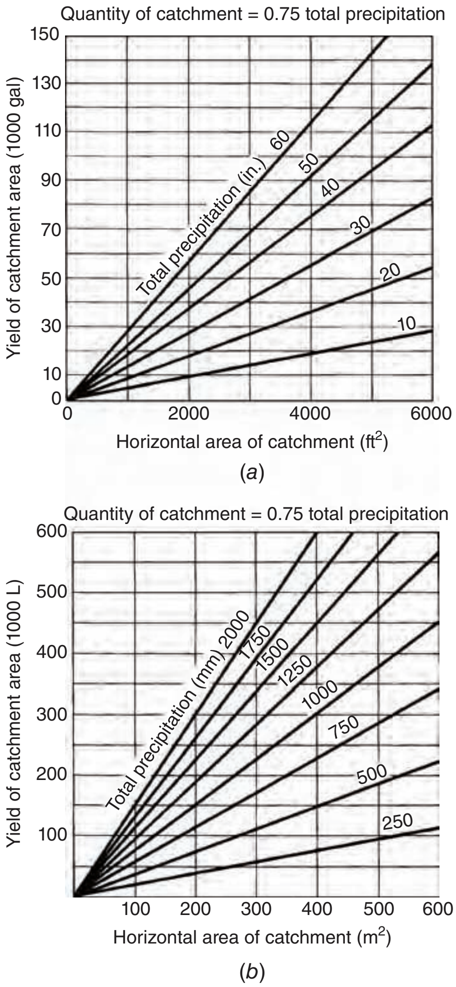


Fig. 18.5 *Yields of rainfall catchment areas (roofs) in terms of total precipitation. In these graphs, 75% of the total precipitation is assumed to be catchable; the remainder is lost to evaporation or spillage. (a) I-P units from the U.S. EPA's Manual of Individual Water Supply Systems, 1975. (b) SI units (1 m^3 = 1000 L).*

Assume, being a bit conservative, that up to 200 gpd (760 L/d) of rainwater will be utilized.

Catchment Area: Salem's average annual rainfall is 41 in. (1042 mm). Design rainfall is ⅔ × 41 = 27.3 in. (⅔ × 1042 = 695 mm) in a dry year; the yearly need is 200 gpd × 365 days = 73,000 gal (760 L/d × 365 = 277,400 L). (The combination of 73,000 gal [277,400 L] and 27.3 in. [695 mm] is off the chart in Fig. 18.5a, so divide 73,000 gal [277,400 L] by 2 to obtain 36,500 gal [138,700 L] and then double the resulting catchment area.) At 27.3 in. (695 mm) of precipitation, 36,500 gal (138,700 L) will be caught by 2800 ft^2 (260 m^2). The catchment area for 73,000 gal (277,400 L) is, therefore, 2 × 2800 = 5600 ft^2 (2 × 260 = 520 m^2). (So about 28% of the 20,000-ft^2 [1860-m^2] factory's roof area will suffice for a catchment area.)

Cistern Capacity: Salem normally has very dry summers; average monthly rainfall is as follows:

May	2.1 in. (53 mm)
June	1.4 in. (36 mm)
July	0.4 in. (10 mm)
August	0.6 in. (15 mm)
September	1.5 in. (38 mm)
October	4.0 in. (102 mm)

The dry period, then, runs from mid-June to mid-September—about 90 days. Thus, capacity = 200 gpd × 90 days = 18,000 gal (760 L/d x 90 = 68,400 L):

$$\text{volume} = \frac{18{,}000\ \text{gal}}{7.48\ \text{gal/ft}^3} = 2406\ \text{ft}^3$$

$$\left(\frac{68{,}400\ \text{L}}{1000\ \text{L}/\text{m}^3} = 68\ \text{m}^3\right)$$

(For example, 5 ft deep × 22 ft square = 2420 ft^3 [1.5 m × 6.7 m square = 67 m^3].) A more detailed sizing procedure for this building's cistern is presented later in this chapter. ■

(c) Required Facilities

Another important early design question is: How many plumbing fixtures should be provided? Table 18.3 lists the minimum plumbing facilities required for various types and sizes of building occupancies. (Note that local requirements may differ somewhat from this particular guide, which is taken from the 2012 *International Plumbing Code*. There are many plumbing codes in use in North America, and they sometimes disagree.) Because these are considered minimal requirements, more generous provisions are sometimes appropriate. Chapter 19 discusses the design of the spaces in which these services are used.

(d) Sewage

Where public sewers are available (as in most urban areas), the designer usually is not concerned with estimating the flow of sewage. However, where private or on-site sewage treatment is required, or

TABLE 18.3 Minimum Number of Plumbing Facilities[a]

	Water Closets Urinals[b]					
Occupancy	**Male**	**Female**	**Lavatories**	**Bathtubs/ Showers**	**Drinking Fountains[c]**	**Others**
Assembly						
Theaters	1 per 125	1 per 65	1 per 200	—	1 per 500	1 service sink
Nightclubs	1 per 40	1 per 40	1 per 75	—	1 per 500	1 service sink
Restaurants	1 per 75	1 per 75	1 per 200	—	1 per 500	1 service sink
Halls, museums, etc.	1 per 125	1 per 65	1 per 200	—	1 per 500	1 service sink
Coliseums, arenas	1 per 75	1 per 40	1 per 150	—	1 per 1000	1 service sink
Churches[d]	1 per 150	1 per 75	1 per 200	—	1 per 1000	1 service sink
Stadiums, pools, etc.	1 per 75	1 per 40	1 per 150	—	1 per 1000	1 service sink
Business[e,f,g]	1 per 25		1 per 40	—	1 per 100	1 service sink
Educational	1 per 50		1 per 50	—	1 per 100	1 service sink
Factory and industrial	1 per 100		1 per 100	[h]	1 per 400	1 service sink
High hazard[e,f]	1 per 100		1 per 100	[h]	1 per 1000	1 service sink
Institutional						
Residential care	1 per 10		1 per 10	1 per 8	1 per 100	1 service sink
Hospitals, ambulatory nursing home patients[i]	1 per room[j]		1 per room[j]	1 per 15	1 per 100	1 service sink per floor
Day nurseries, sanitariums, nonambulatory nursing home patients, etc.[i]	1 per 15		1 per 15	1 per 15[k]	1 per 100	1 service sink
Employees, other than residential care[i]	1 per 25		1 per 35	—	1 per 100	—
Visitors, other than residential care	1 per 75		1 per 100	—	1 per 500	—
Prisons[i]	1 per cell		1 per cell	1 per 15	1 per 100	1 service sink
Asylums, reformatories, etc.[i]	1 per 15		1 per 15	1 per 15	1 per 100	1 service sink
Mercantile[e,f,g]	1 per 500		1 per 750	—	1 per 1000	1 service sink
Residential						
Hotels, motels	1 per guestroom		1 per guestroom	1 per guestroom	—	1 service sink
Lodges	1 per 10		1 per 10	1 per 8	1 per 100	1 service sink
Multiple-family unit	1 per dwelling unit		1 per dwelling unit	1 per dwelling unit	—	1 kitchen sink per dwelling unit; 1 automatic clothes washer connection per 20 dwelling units
Dormitories	1 per 10		1 per 10	1 per 8	1 per 100	1 service sink
One- and two-family dwellings	1 per dwelling unit		1 per dwelling unit	1 per dwelling unit	—	1 kitchen sink per dwelling unit; 1 automatic clothes washer connection per dwelling unit[l]
Storage[e,f]	1 per 100		1 per 100	[h]	1 per 1000	1 service sink

Source: Reprinted from the 2012 *International Plumbing Code*, www.iccsafe.org

[a]Based on one fixture being the minimum required for the number of persons indicated or any fraction of the number of persons indicated. The number of occupants shall be determined by the building code. Unless otherwise shown, the required water closets, lavatories, and showers or bathtubs shall be distributed evenly between the sexes based on the percentage of each sex anticipated in the occupant load. The occupant load shall be composed of 50% of each sex, unless statistical data approved by the code official indicate a different distribution.

[b]In each bathroom or toilet room, urinals shall not be substituted for more than 50% of the required water closets.

[c]Drinking fountains shall not be installed in public restrooms. Where water is served in restaurants or where bottled water coolers are provided in other occupancies, drinking fountains shall not be required.

[d]Fixtures located in adjacent buildings under the ownership or control of the church shall be made available during the periods the church is occupied.

[e]Separate employee facilities shall not be required in occupancies in which 15 or fewer people are employed. Separate facilities for each sex shall not be required in structures or tenant spaces with a total occupant load, including both employees and customers, of 15 or fewer in which food or beverage is served for consumption within the structure or tenant space.

TABLE 18.3 Minimum Number of Plumbing Facilities (*Continued*)

[f]Access to toilet facilities in occupancies other than assembly or mercantile shall be from within the employees' regular working area. The required toilet facilities shall be located not more than one story above or below the employees' regular work area, and the path of travel to such facilities shall not exceed a distance of 500 ft (152 m).

[g]In mercantile and assembly occupancies, employee toilet facilities shall be either separate facilities or public customer facilities. Separate employee facilities shall not be required in tenant spaces of 900 ft^2 (84 m^2) or less where the travel distance from the main entrance to a central toilet area does not exceed 500 ft (152 m) and where such central facilities are located not more than one story above or below the tenant space.

[h]Emergency showers and eyewash stations shall be provided with a supply of cold water as required by the manufacturer. Waste connection shall not be required for emergency showers and eyewash stations.

[i]Toilet facilities for employees shall be separate from facilities for inmates or patients.

[j]A single-occupant room with one water closet and one lavatory serving not more than two adjacent patient rooms shall be permitted where such room is provided with direct access from each patient room and with provisions for privacy.

[k]For day nurseries, a maximum of one bathtub shall be required.

[l]For attached one- and two-family dwellings, one automatic clothes washer connection shall be required per 20 dwelling units.

where public sewage treatment facilities are overtaxed, total sewage flow is an early design concern. Table 18.4 lists these sewage flows by type of occupancy, again in g/cd (L/cd). Note that sewage flow may differ from supply flow, especially where supply water is used for irrigation, for car washing, or in evaporative processes.

Once the daily flow of sewage is established, some early guidelines are needed for determining the suitability of and the area required by some treatment processes. One of the most common reasons for the rejection of a potential rural building site is a lack of suitability for sewage disposal. A geologic analysis of structural and sewage disposal potential is one of the first documents needed by the designer. Chapter 20 describes the sizing of some common treatment methods. At this earlier stage, the following design guidelines can be useful:

Septic Tank Drainfields. In I-P units (minimum 750-ft^2 area for any system):

- For shallow trenches in poorly draining soil: drainfield area = total sewage flow in gpd × 3.6 ft^2/gal
- For deep trenches in well-draining soil: drainage area = total sewage flow in gpd × 0.4 ft^2/gal

In SI units (minimum 70-m^2 area for any system):

- For shallow trenches in poor soil: L/day × 0.087 m^2/L
- For deep trenches in good soil: L/day × 0.01 m^2/L

(These guidelines allow for an expansion area equal to the original size of the drainage field in case of field failure.)

Mounds. These are built-up leaching fields on top of the existing grade (see Fig. 20.38). For a single-family dwelling, allow for a 4-ft-high (1.2-m-high) mound whose bottom area is a square, 44 ft (13.4 m) on each side and whose sides slope at a 1:3 vertical-to-horizontal ratio.

Package Sewage Plant Drainfields. In these, sewage is treated to a much greater extent than in septic tanks, and effluent is filtered:

- In poorly draining soil: total sewage flow in gpd × 0.49 ft^2/gal (L/day × 0.012 m^2/L).
- In well-draining soil: total sewage flow in gpd × 0.23 ft^2/gal (L/day × 0.006 m^2/L).

Sewage Lagoons. These consist of at least two open treatment ponds (primary and secondary) and are sized on the basis of pounds of biochemical oxygen demand (BOD) rather than gallons of sewage flow. A typical assumption for estimating BOD is:

- 0.2 lb (91 g) BOD/person for ordinary domestic sewage
- 0.3 lb (136 g) BOD/person where garbage grinders or other devices contribute added organic material to domestic sewage

The *total* land area required for the two ponds can be estimated as:

- 20 lb BOD/acre (22 kg BOD/hectare) for the (colder) northern United States
- 35 lb BOD/acre (39 kg BOD/hectare) for the (drier, warmer) southern United States

(The primary pond is usually sized for 50 lb BOD/acre [56 kg BOD/hectare].)

Table 18.4 Estimated Sewage Flow Rates

Type of Occupancy	"Unit" Gallons (Liters) per Day
Airports	15 (56.8) per employee
	5 (18.9) per passenger
Auto washers	Check with equipment manufacturer
Bowling alleys (snack bar only)	75 (283.9) per lane
Camps, campgrounds with central comfort station	35 (132.5) per person
Campgrounds with flush toilets, no showers	25 (94.6) per person
Day camps (no meals served)	15 (56.8) per person
Summer and seasonal	50 (189.3) per person
Churches (sanctuary)	5 (18.9) per seat
With kitchen waste	7 (26.5) per seat
Dance halls	5 (18.9) per person
Factories, no showers	25 (94.6) per employee
With showers	35 (132.5) per employee
Cafeteria, add	5 (18.9) per employee
Hospitals	250 (946.3) per bed
Kitchen waste only	25 (94.6) per bed
Laundry waste only	40 (151.4) per bed
Hotels (no kitchen waste)	60 (227.1) per bed (2 person)
Institutions (resident)	75 (283.9) per person
Nursing home	125 (473.1) per person
Rest home	125 (473.1) per person
Laundries, self-service	50 (189.3) per wash cycle
Commercial	Per manufacturer's specifications
Motel	50 (189.3) per bed space
With kitchen	60 (227.1) per bed space
Offices	20 (75.7) per employee
Parks, mobile homes	250 (946.3) per space
Picnic parks (toilets only)	20 (75.7) per parking space
Recreational vehicles, without water hook-up	75 (283.9) per space
With water and sewer hook-up	100 (378.5) per space
Restaurants/cafeterias	20 (75.7) per employee
Toilet	7 (26.5) per customer
Kitchen waste	6 (22.7) per meal
Add for garbage disposal	1 (3.8) per meal
Add for cocktail lounge	2 (7.6) per customer
Kitchen waste-disposal service	2 (7.6) per meal
Schools—staff and office	20 (75.7) per person
Elementary students	15 (56.8) per person
Intermediate and high	20 (75.7) per student
With gym and showers, add	5 (75.7) per student
With cafeteria, add	3 (11.4) per student
Boarding, total waste	100 (378.5) per person
Service station, toilets	1000 (3785) for 1st bay
	500 (1892.5) for each additional bay
Stores	20 (75.7) per employee
Public restrooms, add (per unit of floor space)	1 per 10 ft^2 (4.1 per m^2)
Swimming pools, public	10 (37.9) per person
Theaters, auditoriums	5 (18.9) per seat
Drive-in	10 (37.9) per space

Source: ©2012 *Uniform Plumbing Code*; Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

18.4 RAINWATER

There is a striking similarity between rainwater and solar energy. Both are essential for agriculture, and both have been well understood and utilized by farmers since agrarian societies first emerged. Both can be very beneficial to architecture and were utilized as needed by anonymous builders for centuries. Both fell out of favor with designers as plentiful supplies of pure, centrally treated water and concentrated, centrally controlled fuels became commonplace. Both are thinly, yet relatively evenly, spread over the world's population, so they are at least seasonally available to help meet nearly every building's needs for water and heat. Yet both are difficult to utilize in industrialized societies, because they require *individual preoccupancy* expenditures.

Consider the typical public water and electric utility in a U.S. city. It can raise the funds to build large water treatment plants, electricity-generating plants, and the network of pipes and wires that bring these commodities to every building. The utility's costs, including interest on its construction debts, will be passed on to its consumers on a monthly basis, along with a margin of profit that is usually controlled by state governments. Thus, our society has a well-established method for encouraging central suppliers of water and power.

Now consider the individual building owner. To build a cistern and a solar-heated building, she must borrow money at an interest rate higher than that which the utility pays, and both options cost more initially than simple connections to the utility's pipes and lines. Even though she is willing to flush her toilets with rainwater rather than with chlorinated and filtered potable water from the utility, and even though she is willing to heat with lower-grade solar energy rather than with higher-grade electricity, she must pay a substantial first-cost penalty—with interest—to do so.

The overall public good could be well served by a mixture of public networks of pure water and electricity, combined with individual cisterns and solar applications. The environmental benefits would be substantial: less water withdrawn from rivers, lakes, and underground aquifers; less energy and chemicals used to treat and deliver such water; less storm water discharged to pollute rivers; less fuel used to generate electricity; and less environmental damage from power plants. Yet we continue to economically discourage the individual who uses the rain and the sun.

Architects Fernau and Hartman's design for an invited competition for a "low-entropy kindergarten" in Frankfurt, Germany (Fig. 18.6), celebrates

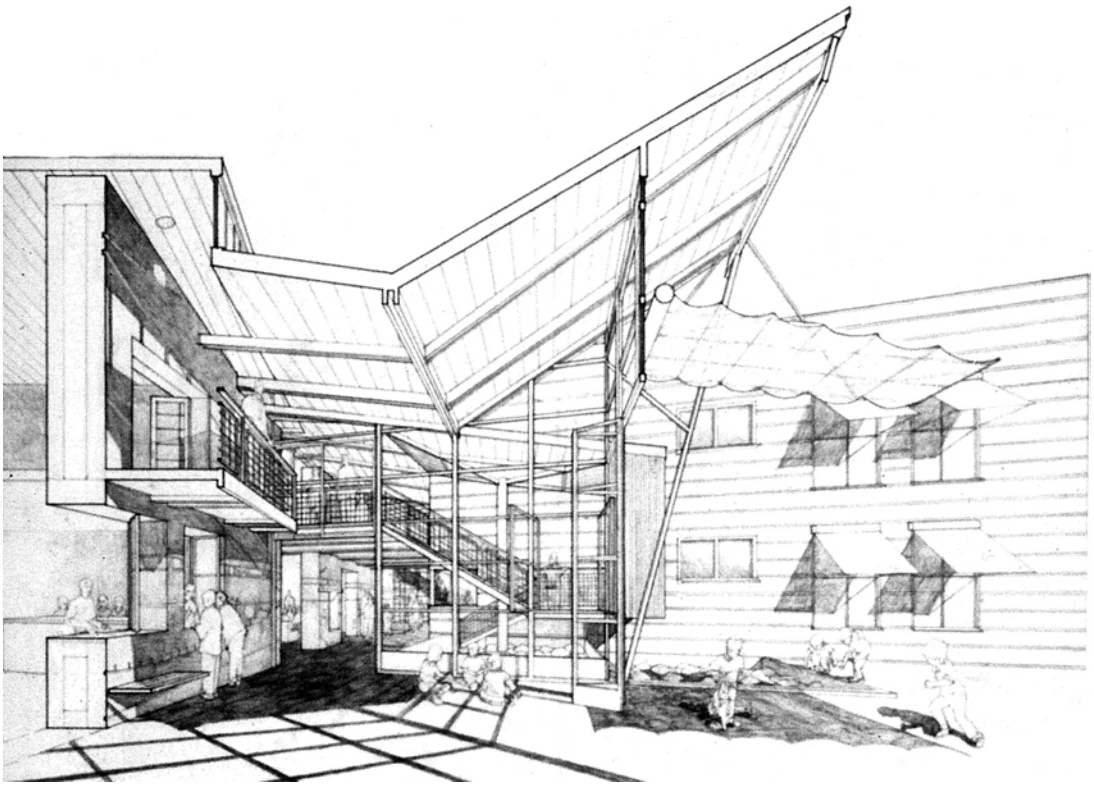


Fig. 18.6 *This low-entropy kindergarten competition entry for Frankfurt, Germany, features sun, adjustable shade, and a roof that collects rainwater and leads it to an interior stone-filled catchment. The rainwater downspout can be seen in the center of the drawing; the stone-filled catchment is below the stair landing. The overflow then goes outside, through a layer of stones and into a belowground cistern. (Courtesy of Fernau & Hartman, Architects, Berkeley, CA.)*

sun and rainwater as teaching elements. In their words, "The building reveals natural phenomena such as the play of light and shadow over a wall during the course of a year, the warmth of a wintergarden in January, the cooling shade from deciduous vines on a trellis overhead, water pouring off the roof into an interior stone catchment during a downpour."

18.5 COLLECTION AND STORAGE

In terms of both quality and quantity, rainwater is an attractive alternative. Figure 18.4*b* shows that rainwater is close to the purest state in the hydrologic cycle. More recently, it is true, air pollution has begun to threaten the quality of rainwater in some areas as acid rain has become widespread in the northeastern section of the North American continent and in Europe. In some particularly air-polluted locations, lead poses a threat to rainwater quality. Also, on any catchment surface, dust and bird droppings are common pollutants that must be considered. Other factors that bear on rainwater quality are roofing materials and the form of the roof. The appropriate health authority should be consulted for a list of roofing materials that will have no toxic effects on rainwater. Steeper roofs are scoured by winds, and thus collect less dust and give cleaner runoffs. Devices to discourage roosting birds are strongly recommended, as are periodic checks of cistern water for bacteria. Fungicides (for moss control) should be scrupulously avoided, as should roofing paints containing lead. For these reasons, urban rainwater commonly is not used for drinking and cooking. (Bottled water or on-site water distilling can supply potable water.) For the typical residence, however, that still leaves about 95% of indoor water usage that could be provided by rainwater. Also, in those cities that have very "hard" public water supplies, rainwater's "soft" characteristics make it particularly attractive.

The quantity of rainwater available in most U.S. locations could meet a high percentage of typical home or business needs. Milne (1976) pointed out that the 42 in. (1067 mm) of rain that falls annually on the streets and roofs of Manhattan Island could, if collected and stored, provide 148% of the residential needs of its 1.7 million inhabitants. For the typical U.S. suburban house, with a roof area of 1500 ft^2 (139 m^2), the annual catchment can be estimated by combining the rainfall quantities (Fig. 18.7) with the resulting catchment yield (Fig. 18.5). Even at a "dry" rate of only 20 in.

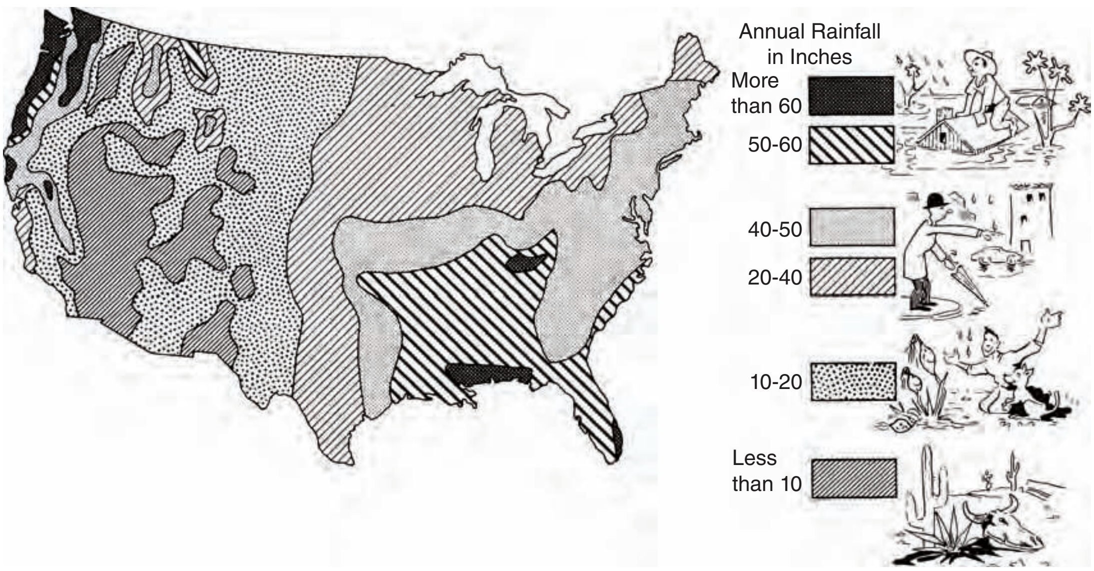


Fig. 18.7 *Annual rainfall in the United States. Cistern volume conversion factors:*

1 ft^3 = 7.48 gal = 0.02832 m^3
1 m^3 = 1000 L = 264.2 gal

(508 mm) annually, a 1500-ft^2 (130-m^2) roof would yield about 12,000 gal, or 33 gpd (45,424 L, or 124 L/d)—nearly enough to meet the clothes-cleaning and dishwashing needs of the family.

Unfiltered rainwater seems particularly well suited to the irrigation of small lawns or gardens, both because it lacks additives unneeded by plants, such as chlorine and sodium fluoride, and because it can reduce the user's demand on the public water supply on the hottest summer days. Cisterns located above an irrigated area have the advantage of replacing a pump with simple gravity flow. A rain barrel at the bottom of a downspout is an example of this approach—although one of limited capacity.

In many of the world's drier areas, small cisterns within a home are common. Such cisterns, which can be fed both by rainwater and by the public supply, are frequently used for all domestic purposes, including drinking. The presence of such a large water volume also can be advantageous in the event of fire. Sometimes these storage cisterns are required because the public supply is diminished or cut off at peak usage hours due to insufficient water main capacity. Figure 18.8 shows a cistern in a typical outdoor location, along with various options by which pollution from dirty roofs can be minimized.

When cisterns are taken seriously as water storage devices, their function and size can become strong design-form determinants. The country home of architect John Andrews in the dry ranchland of New South Wales, Australia, offers a particularly striking example of cisterns used as form-producing elements (Fig. 18.9). These demonstrate the design image of "pregnant downspouts" storing water above the area where it will be used rather than belowground. The corner rainwater collectors also help deflect cooling summer breezes into the house along the diagonal walls at each corner. The central skylight then vents the breezes, along with the house's heat. From the corner cisterns, rainwater is pumped up to the central tower's storage tank. It then can be heated by solar collectors (to be installed on the sloping top of the tower), or used to supply the house's plumbing fixtures, or even used to sprinkle the metal roof surface, whose surface temperature could quickly be lowered by evaporation. Unevaporated roof water simply runs back into the cisterns. As a final design-with-water gesture, the shower (off bedroom 1) has been made into a true celebration place for cleansing and refreshing, with a sweeping view of the ranch.

In this passively solar-heated home, the living areas are placed on the elongated north side—the warmer side in the cold season for this southern hemisphere house. Passive cooling is aided by pergolas on the west and south, which are covered with vines for hot season shading of windows.

Sizing. The procedures described in Section 18.3 are for rough sizing of both the catchment area and the storage capacity for cisterns. When rainwater is to be a primary, as opposed to merely a supplementary, source, a closer look must be taken at rainfall deposits and user withdrawals from a cistern.

This procedure depends on the monthly average rainfall (from NOAA Local Climatological Data), the monthly water usage, and the catchment area yield (from Fig. 18.5).

EXAMPLE 18.1, PART B Take a closer look at the cistern that was approximately sized in Part A. Daily usage for this cistern, to be used for toilet flushing in a factory near Salem, Oregon, was estimated at 200 gal (760 L) and the catchment area at 5600 ft^2 (520 m^2). The cistern capacity was estimated at 18,000 gal (68,400 L). Begin the process in the midst of the wettest months.

From Table 18.5, the following conclusions can be drawn:

1. For an 18,000-gal (68,400-L) cistern, when the end-of-December cumulative capacity is added to January's surplus, the cistern will be at capacity from November through April.
2. With no allowances for abnormally dry months, we could reduce the cistern size by about 3000 gal [11,355 L] (the size of the smallest cumulative capacity in September).
3. A larger cistern—one that could utilize everything from the catchment area—could be built. Its approximate size would be the year-end surplus of 38,510 gal (145,760 L) plus the maximum spring monthly cumulative capacity of 25,410 gal (96,177 L) in April.
4. Alternatively, the surplus could be devoted to additional usage of rainwater, beyond mere toilet flushing, from November through April. ■

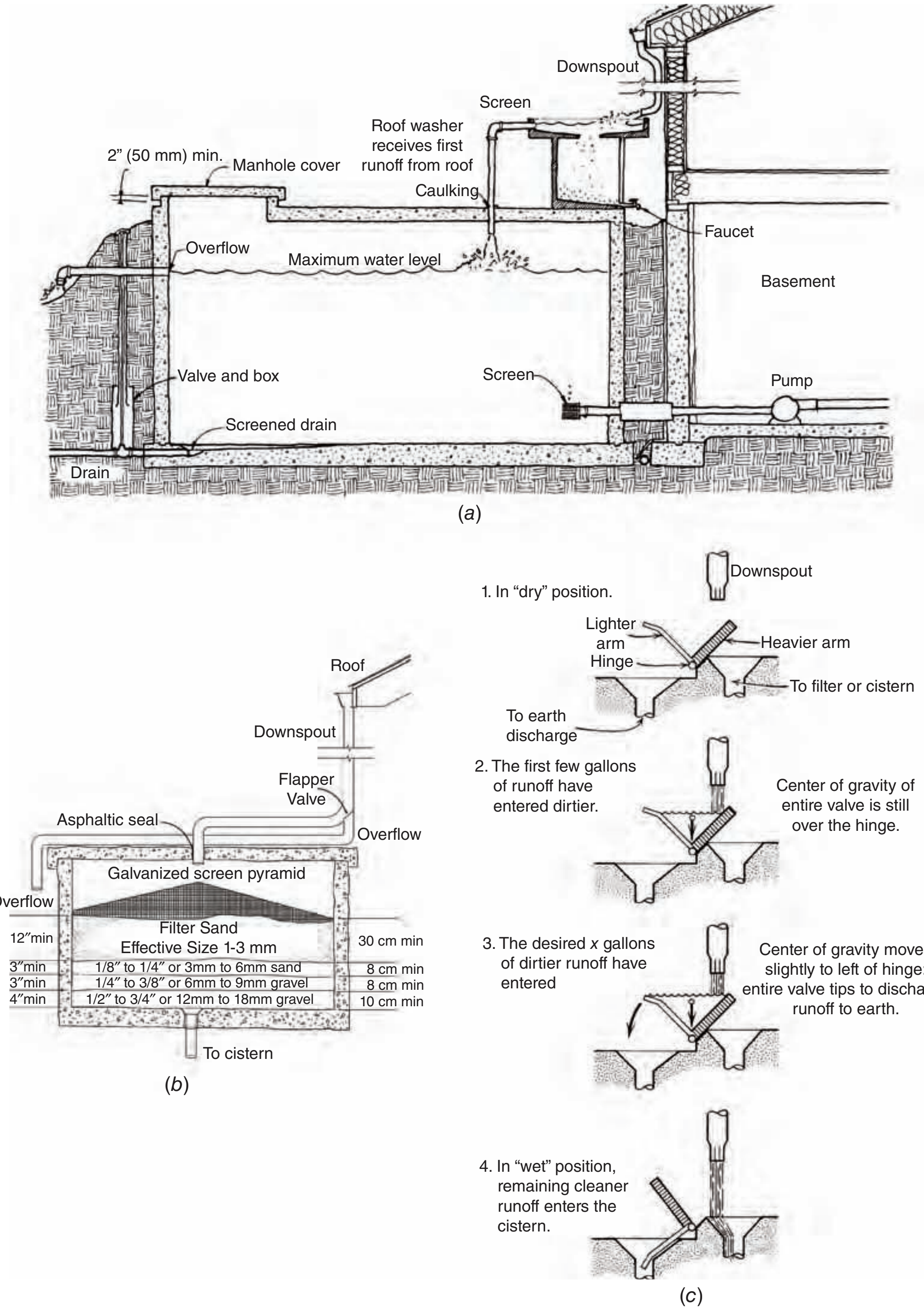
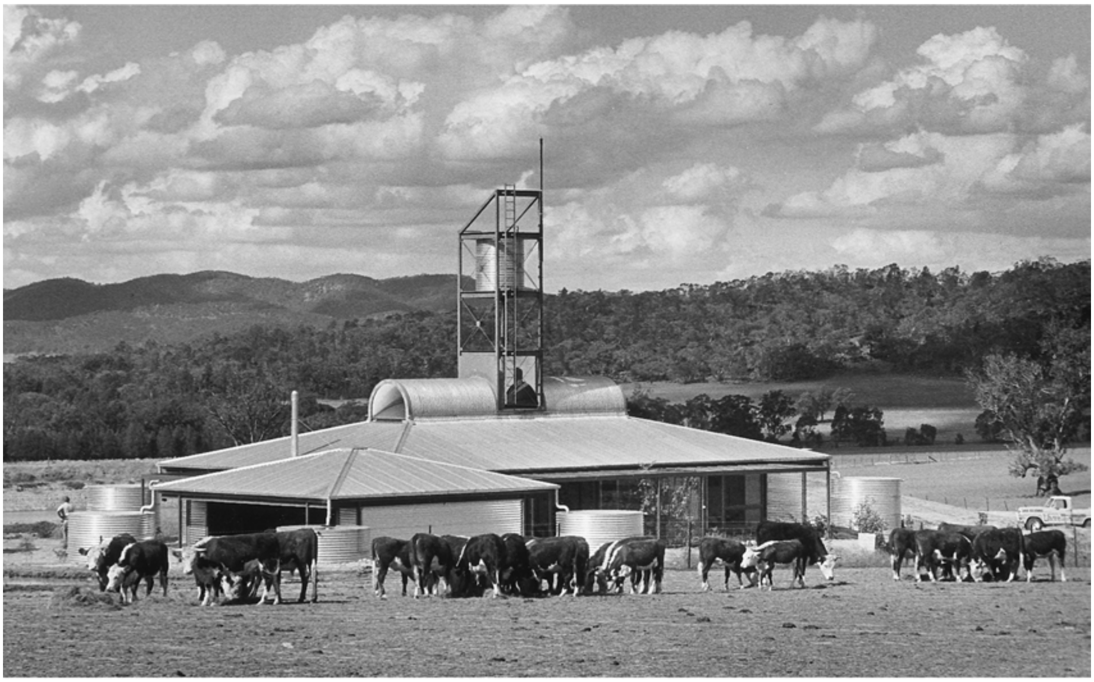


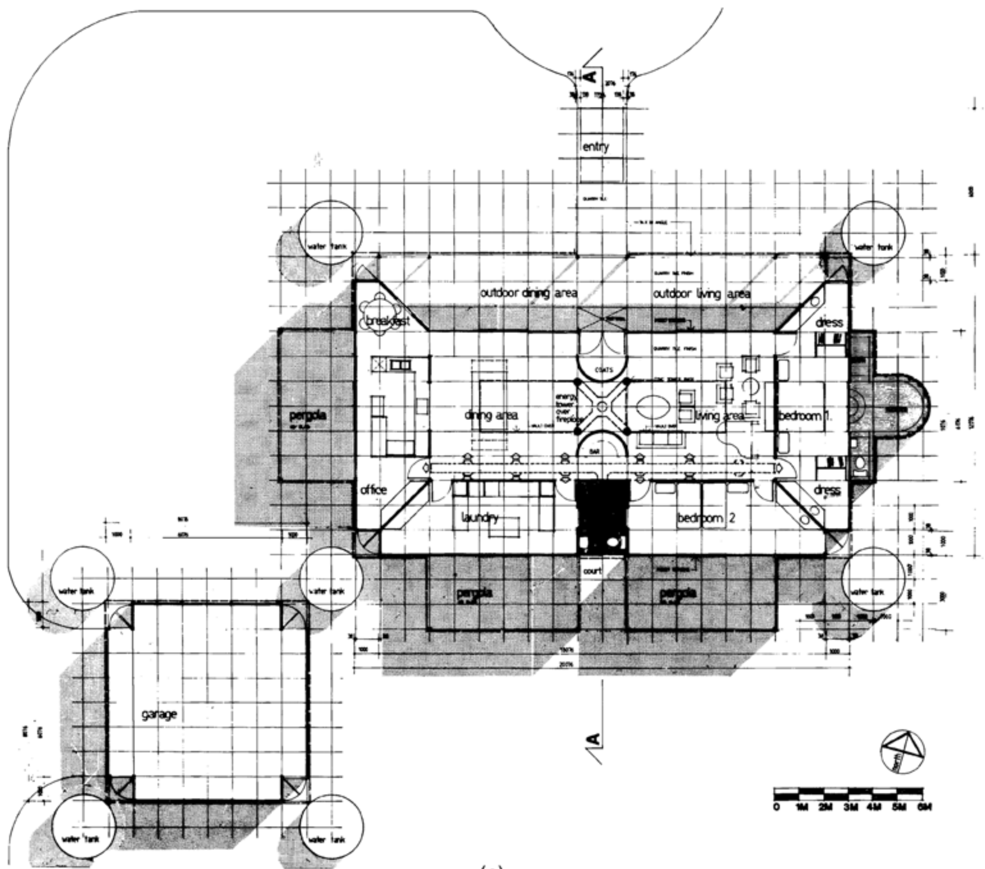
Fig. 18.8 *Section through a typical outdoor cistern. (a) A "roof washer" gets the dirtiest first runoff from the roof. It can later be emptied either by opening the faucet wide or by leaving the faucet slightly open so that it will slowly drain. (b) In place of the roof washer, a sand filter may be used. The "flapper valve" is used rarely, to divert the first rainfall after a prolonged dry spell. After this, the valve is left in a position to divert all rainwater to the sand filter. (Redrawn with SI units by Nathan Majeski; based upon the U.S. EPA's* Manual of Individual Water Supply Systems, *1975.) (c) Another roof-washing option is a "tipping valve," which dumps the first few gallons of each rainfall. After each rainfall, the valve must be manually (or spring) reset to the "dry" position if it is to again intercept dirty water. In an extended wet period, it would probably be left in the "wet" position.*



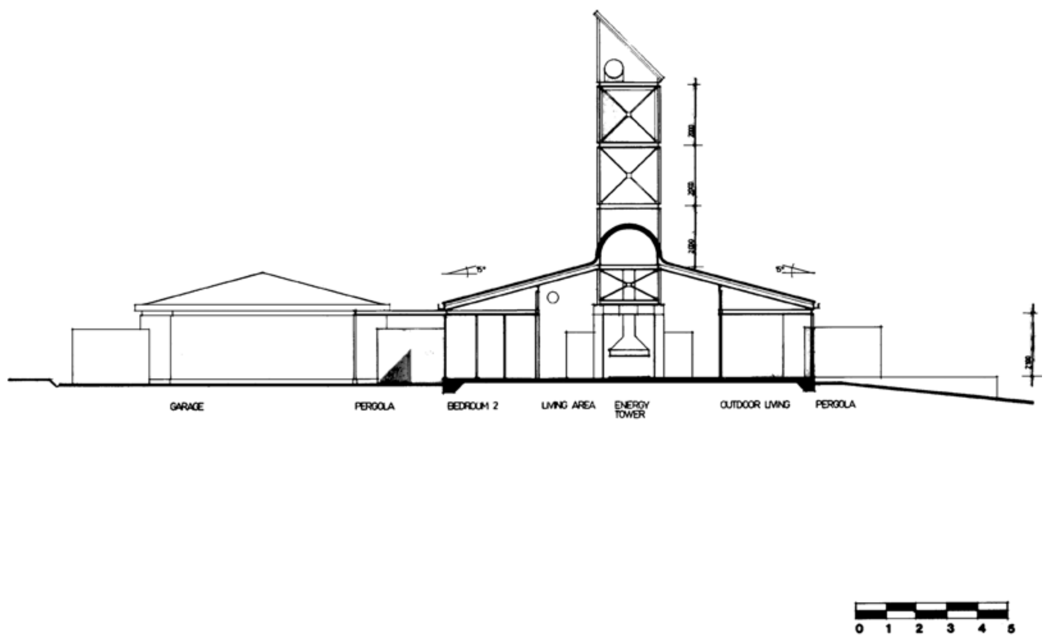
(a)

(b)

Fig. 18.9 *Country home of architect John Andrews, Eugowra, New South Wales, Australia. (a) View from the southwest showing corner cisterns, the central daylight/ventilation barrel vault, and the "energy tower" with a water storage tank. (b) View from the south showing the shading pergola to be covered by vines. (c) Floor plan showing the fireplace at the center and cisterns at all corners. (d) Section through the living area. (Courtesy of John Andrews International Pty, Ltd.)*



(c)



(d)

Fig. 18.9 (Continued)

TABLE 18.5 Rainfall Cistern Sizing Procedure

I Month and Rainfall[a] in. (mm)		II Catchment Yield[b] gal (L)	III Usage[c] gal (L)	IV Net[d] gal (L)	V Cumulative Capacity[e] gal (L)	VI Cumulative Capacity Adjusted for Actual Size[f] gal (L)
January	6.9 (175)	18,630 (70,515)	6200 (23,476)	12,430 (47,048)	12,430 (47,048)	12,430 (47,048)
February	4.8 (122)	12,960 (49,054)	5600 (21,196)	7300 (27,631)	19,790[g] (74,905)	18,000 (68,130)
March	4.3 (109)	11,610 (43,944)	6200 (23,476)	5410 (20,477)	25,200[g] (95,382)	18,000 (68,130)
April	2.3 (58)	6210 (23,505)	6000 (22,710)	210 (795)	25,410[g] (96,177)	18,000 (68,130)
May	2.1 (53)	5610 (21,234)	6200 (23,476)	−530 (−2006)	24,880[g] (94,171)	17,470 (66,124)
June	1.4 (36)	3780 (14,307)	6000 (22,710)	−2220 (−8403)	22,660[g] (85,768)	15,250 (57,721)
July	0.4 (10)	1080 (4088)	6200 (23,476)	−5120 (−19,379)	17,540 (66,389)	10,130 (38,342)
August	0.6 (15)	1620 (6132)	6200 (23,476)	−4580 (−17,335)	12,960 (49,054)	5550 (21,007)
September	1.5 (38)	4050 (15,329)	6000 (22,710)	−1950 (−7381)	11,010 (41,673	3600 (13,626)
October	4.0 (102)	10,800 (40,878)	6200 (23,476)	4600 (17,411)	15,610 (59,084)	8200 (31,037)
November	6.1 (155)	16,470 (62,339)	6000 (22,710)	10,470 (39,629)	26,080[g] (98,713)	18,000 (68,130)
December	6.9 (175)	18,630 (70,515)	6200 (23,476)	12,430 (47,048)	38,510[g] (145,760)	18,000 (68,130)

Source: Based upon procedure from Brown, Reynolds, Ubbelohde *InsideOut: Design Procedures for Passive Environmental Technologies*, © 1982 by John Wiley & Sons.

[a]NOAA data for Salem, Oregon.

[b]From Fig. 18.5, according to which 10 in. (254 mm) of precipitation yields about 27,000 gallons (102,200 L) for this 5600-ft^2 (520-m^2) catchment area.

[c]The factory uses 200 gpd (760 Lpd) times days in each month.

[d]Col. II minus col. III.

[e]Values in col. IV, added month by month.

[f]Set at 18,000 gal (68,130 L) for the factory in Example 18.1.

[g]The cumulative capacity exceeds the actual storage capacity of 18,000 gal (68,130 L).

18.6 RAINWATER AND SITE PLANNING

Prior to the spread of buildings, streets, roads, and paved parking lots to rural areas, water from rainfall and melting snow found its own route to natural destinations. Surface flow to creeks, streams, and rivers accounted for part of this drainage. Underground flow aided the general runoff. Outcropping of flowing groundwater created springs and artesian wells. Low, dished areas formed lakes that in turn overflowed to outlet streams. Flat areas sometimes developed into swamps or marshes.

At a time when there was a choice of locations for towns and villages, sites next to rivers were usually chosen. The waterways provided transportation, and water was supplied from the river or from adjacent wells. As streets and roads were built, slopes could be arranged whereby the rain falling on these areas and flowing onto them from roofs of buildings could run to the river. At interior parts of the country, high ground was favored for building sites and growing communities. Swampy or marshy ground would not be chosen, but did provide terminal locations for storm water that ran off the high ground. In the course of this natural flow, much of the water was drawn by evaporation to the clouds. The rest, conforming to topographic river basins, continued to seek its way to larger bodies of water.

As building increased, desirable locations grew scarce. The possibility of selecting high, dry ground diminished. Large areas, formerly low and marshy, were filled in and buildings constructed, often on piles. From such locations storm water could not be diverted to some adjacent lower area via drainage, or even recharged to the earth through dry wells. Moreover, extensive grids of paved streets and sidewalks in these level developments caught and held the water, resulting in considerable "ponding." Storm sewers had to be built and the water transported great distances, often having to be lifted at intermediate pumping stations before reaching its destination, which might have been a remote river.

This emphasis on the removal of storm water has led to an expensive and elaborate system based on quick disposal of rainfall. By decreasing the time between precipitation and runoff, quick disposal increases the peak flows within such systems, thereby increasing flooding of rivers during storms but reducing the rivers' flow between storms. It also contributes pollutants to waterways that otherwise

TABLE 18.6 Some Constituents of Stream Water

Constituent	Source in Nature	Role in Natural Ecosystem	Source of Urban Excess	Role of Excess
Sediment	Banks of meandering channels	Maintain stream profile and energy gradient; store nutrients	Construction sites; eroding stream banks	Abrade fish gills; carry excess nutrients and chemicals in adsorption; block sunlight; cover gravel bottom habitats
Organic compounds	Decomposing organic matter	Store nutrients	Herbicides; pesticides; fertilizers	Deprive water of oxygen by decomposition
Nutrients	Decomposing organic matter	Support ecosystems	Organic compounds; organic litter; fertilizers; sewage; food waste	Unbalance ecosystem; produce algae blooms; by decomposition deprive water of oxygen
Trace metals	Mineral weathering	Support ecosystem	Cars; construction materials; all kinds of foreign chemicals	Reduce resistance to disease; reduce reproductive capacity; alter behavior
Chloride	Mineral weathering	Support ecosystems	Pavement deicing salts	Sterilize soil and reduce biotic growth
Bacteria	Native animals	Participate in ecosystems	Pet animals; dumpsters; trash handling areas	Cause risk of disease
Oil	Decomposing organic matter	Store nutrients	Cars	Deoxygenate water

Source: Ferguson, B. (1998). *Introduction to Stormwater.* © John Wiley & Sons, New York.

would have been filtered by the soil, as detailed in Table 18.6.

The overloading of storm sewers not only causes minor flooding, but also can influence building design. The designers of the New Orleans Convention and Exhibition Center, a building with 610,000 ft^2 (56,670 m^2) of roof area, spared the city's storm sewers from the impact of a 14-acre (5.7-hectare) runoff by carrying the rainwater over the roofs of adjoining wharfs and discharging it directly into the Mississippi River.

As urban storm sewers reach capacity and suburban groundwater levels drop, designers have begun to emphasize (Fig. 18.10) storm water infiltration (or recharge of groundwater) rather than quick runoff. Three design strategies for encouraging such recharge have emerged: roofs that will retain water and slowly release it, porous pavement, and onsite infiltration of runoff.

(a) Roof Retention

If storm water is to be sent to storm sewers or to soak into the ground, a *slow flow* from roofs will help by diminishing peak flows in sewers and giving soaked soil more time to absorb the runoff. A nearly flat roof with specially designed drains (see Fig. 18.23) forms a temporary pond that permits slower discharge, yet eventually drains completely dry (to discourage mosquito breeding, etc.). For cisterns, however, sloped roofs should be used, as they stay cleaner than flat roofs. Another option is to store the "cistern" water on the roof itself (Fig. 18.11). Another slow flow possibility is a sod roof that will retain water for longer periods than ponded flat roofs.

However achieved, this temporary pond on top of a building will clearly require additional structural reinforcement. Another problem could be posed by high winds blowing sheets of water onto people below. In summer, however, a flooded roof can provide a significant thermal advantage by greatly lowering daytime roof surface temperatures. Rainfall-retaining roofs are now required in some urban areas with overtaxed storm sewers. Sewer districts frequently charge for storm water runoff; by ponding storm water on site, such charges can be reduced or avoided.

(b) Porous Pavement

To retain rainfall on site, many builders use porous asphalt (Fig. 18.12), porous concrete, "incremental" paving, or open-celled pavers (alternation of


(a)


(b)

Fig. 18.10 *Bioswale at the John E. Jaqua Center for Student Athletes, University of Oregon, Eugene. (a) Upon completion, and (b) after two years of growth. (© Alison Kwok; all rights reserved.; © Tyler Mavichien; used with permission.)*

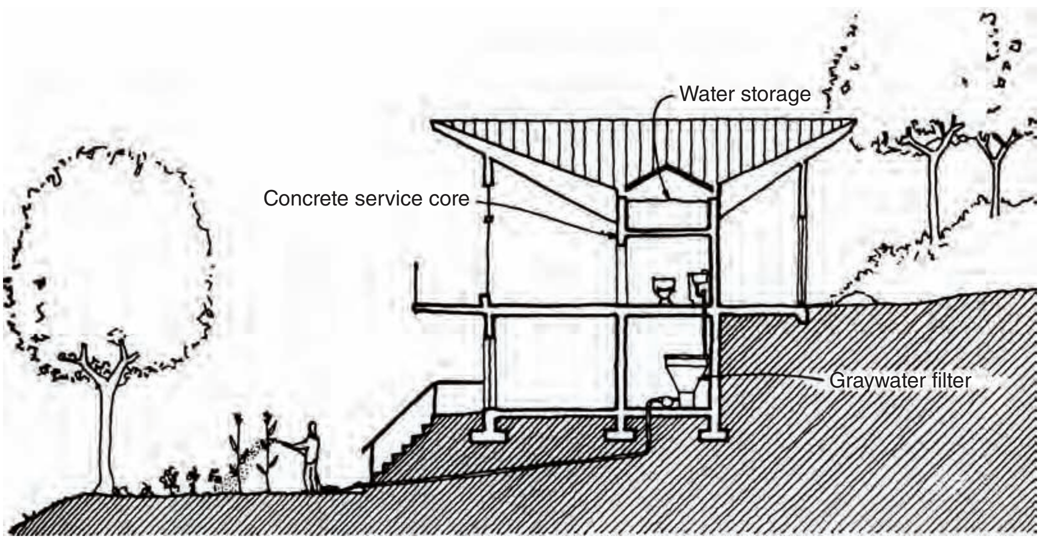


Fig. 18.11 *Retaining rainwater so that gravity flow can encourage its usage.*

paving materials with grass or groundcover plants) for parking lots and roadways.

Porous concrete has been used for many years in building construction as a low-strength, high-porosity material that has some insulating properties (R-5 for 10-in thickness [RSI-0.88 for 254 mm]). Patented porous concrete pavement now in use in Florida has a compressive strength of more than 3800 psi (26,200 kPa) and a permeability of 2.3 gallons of water per minute per square foot (94 L per minute per square meter). (A 2500-psi [17,240 kPa] mix has a permeability of 18.5 gallons per minute per square foot [750 L/m per m^2].) In cold-weather areas, the freeze–thaw cycle could be destructive to porous concrete.

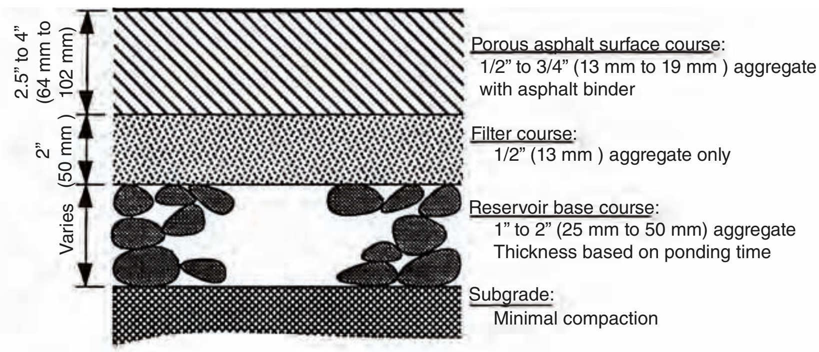
Incremental paving features many small, adjacent paving units; the resulting many joints allow water to pass through more readily than do solid, unbroken surfaces.

Open-celled pavers alternate small concrete or plastic paving units with grass or ground cover, as shown in Fig. 18.13. These are particularly applicable to short-term parking, as for a sports stadium, or for more remote areas of retail mall parking lots. They are also possible for roadway shoulders and emergency-vehicle-only access areas.

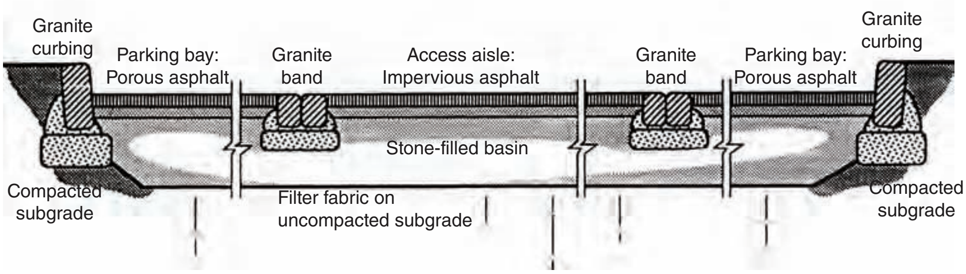
If storm water is not retained, its runoff can be polluted to the extent that treatment is required. Using strips of planting for such treatment (phytoremediation) is discussed at the end of Chapter 20.

(c) Site Design for Recharging

This tactic is especially advisable for suburban-density developments in drier climates with absorptive soil (sand, gravel, etc.). The first option is to implement this at each house; design of entire subdivisions can also be influenced.



(*a*)



(*b*)

Fig. 18.12 *Porous paving encourages groundwater recharge rather than storm runoff. (a) Standard porous asphalt pavement as used in Rockville, Maryland. (b) Subsurface basin allows required retention ponds to serve as parking lots; this example is at the Morris Arboretum in Philadelphia. (Reprinted by permission from B. Ferguson. 1998.* Introduction to Stormwater. *© John Wiley and Sons. Hoboken, NJ.)*

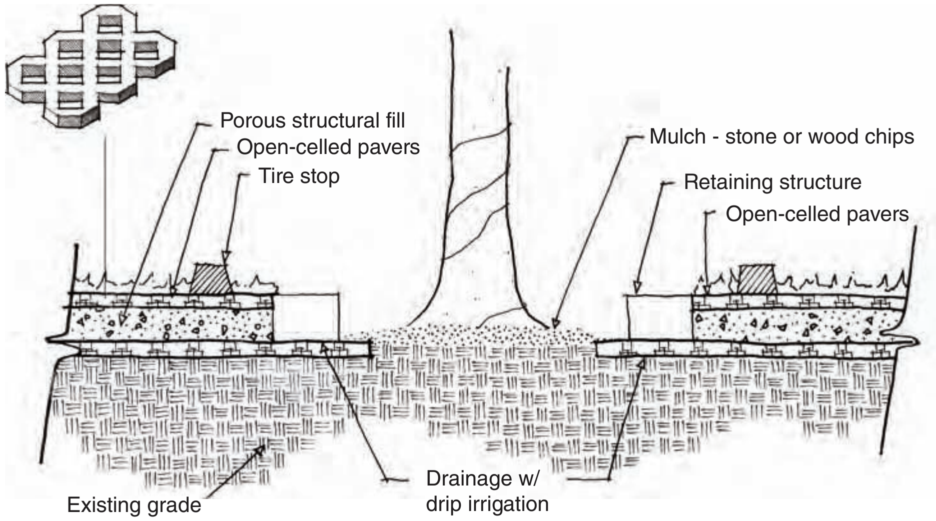


Fig. 18.13 Open-celled pavers on a porous fill allow grass or hardy ground cover to grow within the units. (Drawing by Erik Winter of GrassPave from Invisible Structures, Inc. Information used with permission.)

The simplest design approach is the gutterless sloped roof illustrated in Fig. 18.14, which is applicable to one-story, basement-less homes with wide, overhanging roofs. A gravel-filled trench skirting the perimeter directly below the edge of the eaves catches the water flowing off the roof.

Some designers do not like the appearance of conventional gutters and leaders; other designers celebrate them (Fig. 18.15). There are many ingenious ways to avoid or modify these elements, while still providing proper drainage. In many cases, however, gutters and leaders will

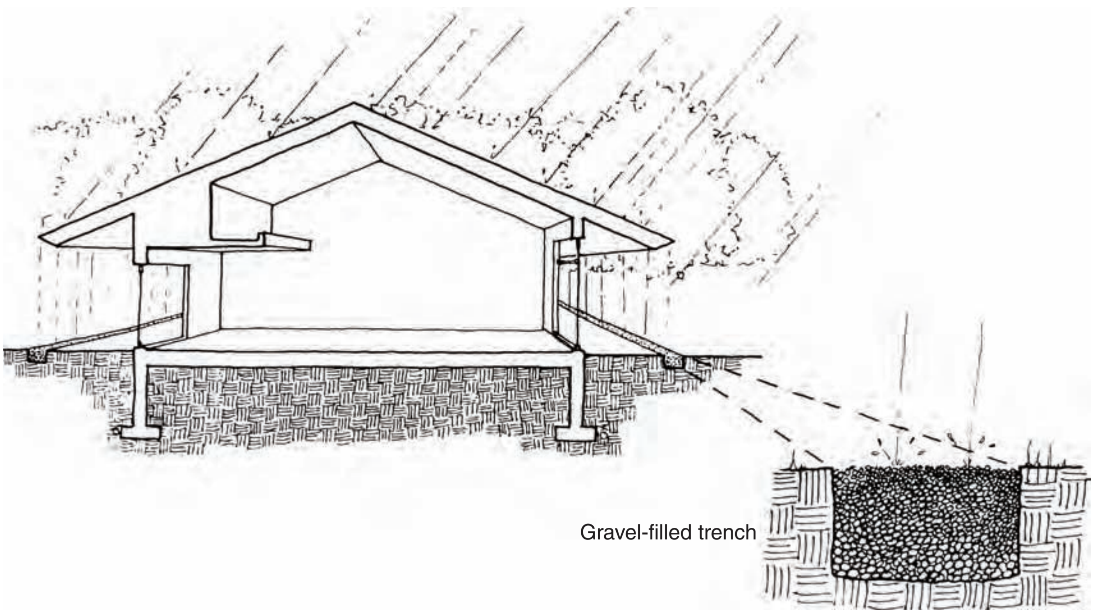


Fig. 18.14 Gutters and leaders are not always essential, provided that doorways, walls, foundations, and landscaped lawns are not subjected to rain concentrations.

be required, either to collect rainwater for cisterns or to control conditions around the perimeter of a house. Several options for storm water recharge can be used with the gutter-leader combination.

A splash pan at the foot of each leader (Fig. 18.16*a*) offers the simplest method. It will lead the water a few feet from the house but will accommodate only a relatively low rate of flow. A gravel-filled pipe is somewhat more effective (Fig. 18.16*b*). When the soil is not very permeable (as, for instance, with clay), it is best to use a dry well with an extended area and many perforations through which the water can be discharged to the ground (Fig. 18.16*c*).

Footing drains are often used to collect and lead away groundwater that accumulates around foundations. This reduces the likelihood of basement wall leakage. These drains are most necessary when higher ground near a building increases the flow of groundwater against underground walls. Figure 18.17 illustrates this and also shows how storm water from drains and roofs may be led to a surface absorption area of rock and gravel, beyond a head wall, where the general storm drain outcrops. This method can be chosen where there is sufficient property area and slope. It has the advantages of easy maintenance and service. Also, one can observe whether it is functioning correctly.

Fig. 18.15 *Rain gutters as an architectural focal point. The Desert Living Center at the Springs Preserve, Las Vegas, features a rain gutter that directs water from the trough of the butterfly roof to a cistern for irrigation. (© Alison Kwok; all rights reserved.)*

In new developments bioswales or recharge basins (Fig. 18.18) are sometimes used to infiltrate storm water into the ground. Water from numerous roofs, paved areas, and curb catch basins is collected and piped to an open, unpaved pit, where it sinks into the earth. This method is not recommended in areas of dense, impervious clay soil. A particularly effective example of this approach is offered by the community of passively solar-heated residences known as Village Homes, outside Davis, California. This area receives only about 20 in. (508 mm) of rain annually, so for this garden-oriented community, the recharge of groundwater was a far more attractive (and less expensive) option than loss of the rainwater to a storm sewer. Storm water flows from leaders to dry, rockbed channels, along which are gardens and bicycle paths (Fig. 18.19). Occasionally, small dams across these channels create temporary holding ponds in case the runoff has not yet soaked through the channel bottom. In the event of extraordinarily heavy rainfall, an inlet to the public storm sewer is available beyond the final holding pond; this inlet is needed approximately once every five years.

The National Wildflower Research Center (Fig. 18.20) is built over an endangered aquifer, southwest of Austin, Texas. This complex of small buildings and larger gardens includes several cisterns, one of which forms the base of a central observation tower. Water gardens and irrigation are both served by the cisterns. The buildings' roofs are designed for rainwater collection, and a small channel (aqueduct) carries water over a wall to the outer cistern.

The planning of the landscape around buildings may closely follow such considerations as irrigation. The *hydrozone* concept of landscape planning is shown in Fig. 18.21. To minimize water consumption, exotic plant species are kept to a minimum and located near the house, where storm runoff and irrigating water are readily available. Native and adapted plantings, which can survive on normal rainfall, are utilized elsewhere. Landscape that requires no additional water is often called a *xeriscape*; see Fig. 19.68, and see Section 19.12 for a discussion of irrigation systems and an example in California's Napa Valley.

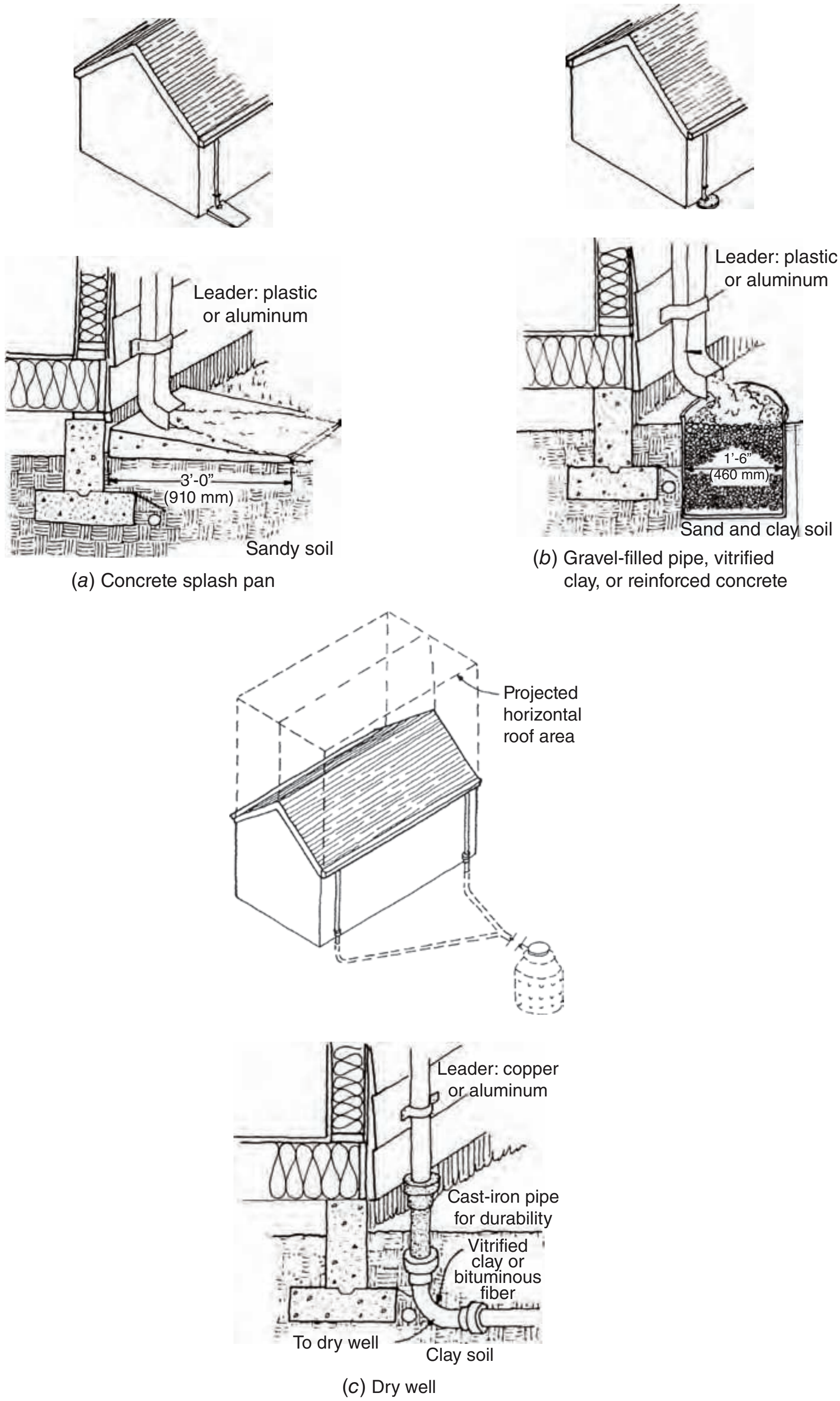


Fig. 18.16 *Roof drainage for houses. Method (a) is suitable for low rates of flow introduced into very pervious soil. When denser soil is encountered, method (b) is used to get the water into the ground and thus avoid surface erosion. For heavy flow or to lead the water farther from the structure, method (c) may be used with one or several dry wells.*

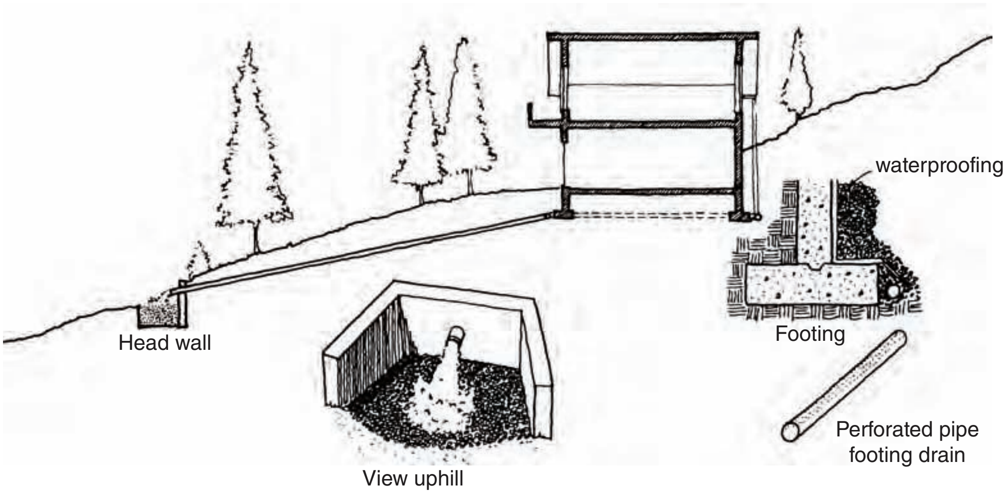


Fig. 18.17 *Disposal of storm water on the site but remote from the house or building. When a wall is against a hill, it is usually subjected to the pressure of groundwater during storms. Open-joint clay, plastic, or fiber tile accepts this water and carries it away. Footing drains are tight-joint clay tile or bituminous fiber pipe. Flow through stone and gravel returns the water to the earth. A head wall is appropriate in lieu of a dry well if the site permits.*

18.7 COMPONENTS

The first design decision to be made for a storm water system involves the establishment of "watersheds" on a building's roof. To what edges, or at what points, will runoff be directed? To what depths will it accumulate before it leaves the roof? Because the answers to these questions depend on the intensity of storms as well as on the roof's geometry, it is necessary to find the maximum hourly rainfall for each location. This figure is available from local building code officials, national climate data archives, or from Fig. 18.22.

Gutters and *leaders* (downspouts) can be sized through the use of Tables 18.7 and 18.8. The sizing of gutters and leaders depends both on the horizontal projected area of the roof, as shown in Fig. 18.16*c*, and on the maximum hourly rainfall.

EXAMPLE 18.2 Select a gutter and two leaders for the front half of a house, as shown in Fig. 18.16. The rainfall rate is 4 in./h (100 mm/h). The projected roof area is 700 ft^2 (65 m^2), and the slope of the gutter (rising $^1/_{16}$ in. per foot of length [5.2 mm per meter of length] is 0.5%.

SOLUTION

From Table 18.7, choose a semicircular gutter with a 6-in. (150-mm) diameter. Note that if a steeper gutter slope were designed, for instance a ½-in. rise per foot of length (4% slope), only a 4-in. (100-mm) diameter gutter would be required.

Because two leaders will be used, each will drain 350 ft^2 (33 m^2). Table 18.8 shows that a 2-in. (50-mm) leader can be used. For this gutter-leader combination, specify the detail of Fig. 18.23*a*.

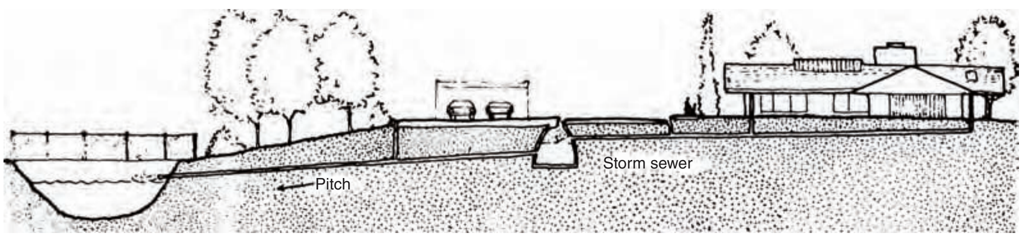
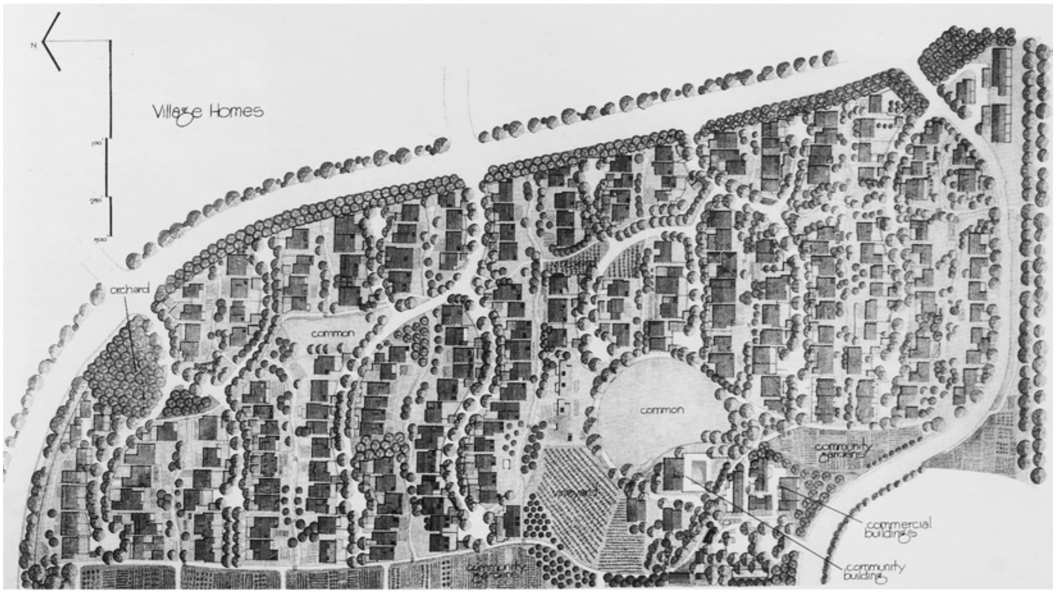


Fig. 18.18 *Recharge basins in suburban communities. When topography, groundwater level, and porosity of the soil permit, developers are sometimes required to install systems that collect storm water and carry it from catch basins at street curbs, the roofs of all houses, and paved areas to a recharge basin that receives the water and returns it to the ground. For the safety of children, a fence is sometimes required to prevent unauthorized access to the basin.*

(*a*)



(*b*)

(*c*)

Fig. 18.19 *Village Homes, a northern California subdivision of solar homes and storm water recharge areas. (a) Photo illustrates the open drainage ways and pedestrian paths. (Photo by Alan Butler.) (b) Plan shows the emphasis on bicycle paths, narrow streets, and widespread community-maintained garden space through which the recharge streambeds are led. (c) Site section explains the gradual drainage from leaders at houses to a recharge stream. (Reprinted by permission from M. Corbett,* A Better Place to Live*; © 1981 by the Rodale Press.)*

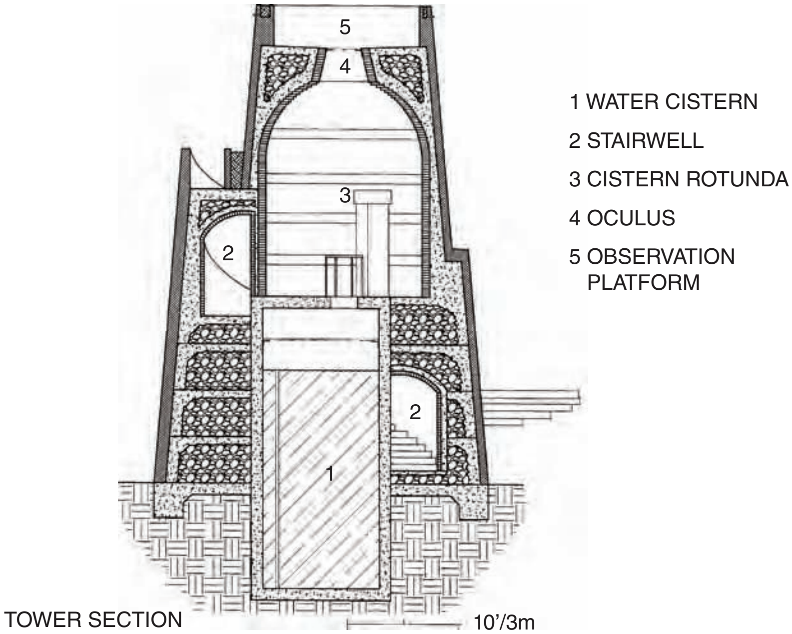


Fig. 18.20 *Section through the observation tower/cistern at the Lady Bird Johnson Wildflower Research Center. (Courtesy of Overland Partners, architects, San Antonio, TX.)*

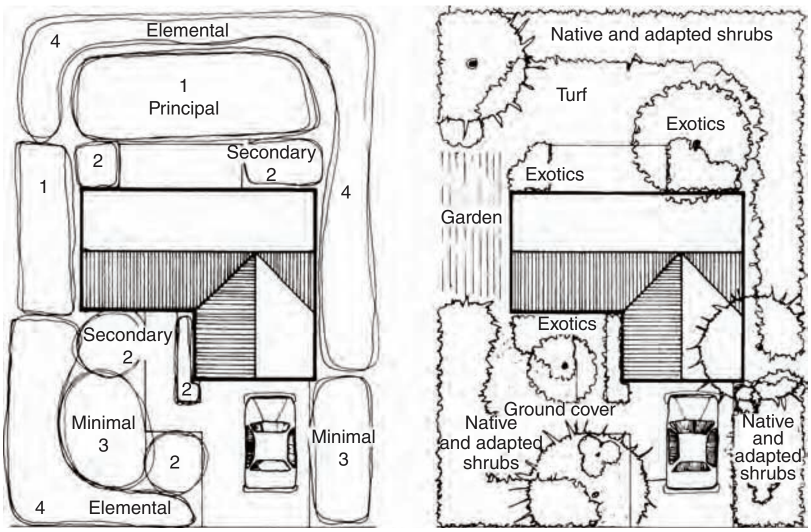
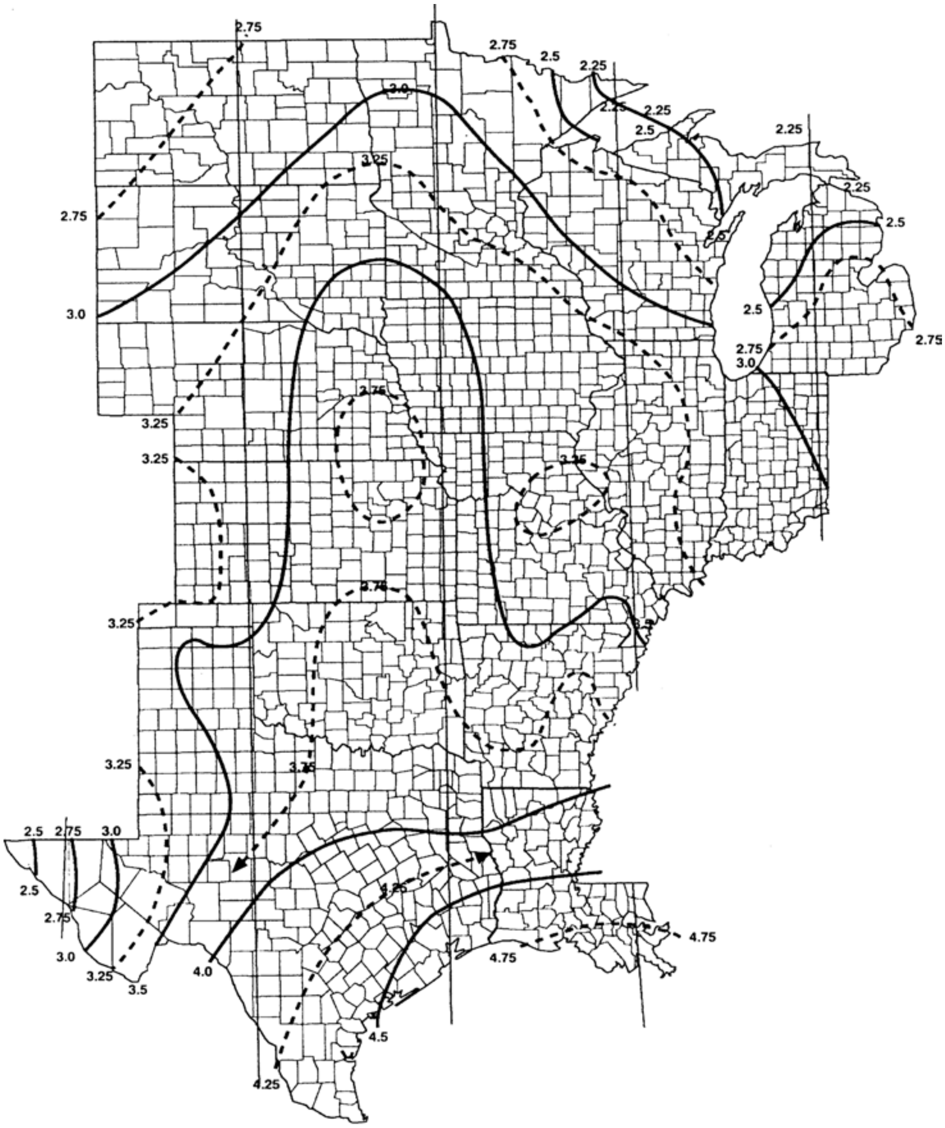


Fig. 18.21 *The hydrozone concept of landscape planning restricts exotic planting to special, easily watered areas. Native and adapted plantings are used elsewhere. Zones are here shown on a typical suburban lot. (Reprinted by permission from* Energy-Conserving Site Design*; E. G. McPherson, ed.; © 1984 by the American Society of Landscape Architects.)*

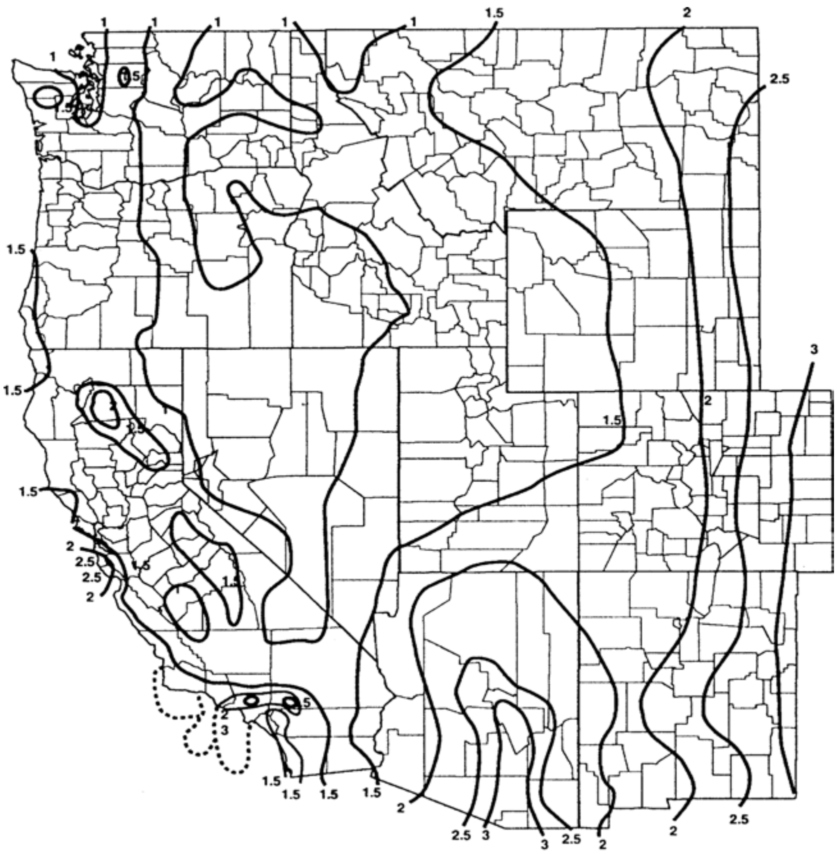
(a)

Fig. 18.22 *Maximum 100-year, 1-hour rainfall (in inches). (a) eastern United States; (b) central United States; (c) western United States. (Note: Alaska, range 0.4 to 1.4 in. [10 to 36 mm]; Hawaii, range 1.5 to 8 in. [38 to 203 mm]) Reprinted from the 2012* International Plumbing Code, *© International Code Council (ICC), Washington, D.C. All rights reserved. www.iccsafe.org*



(b)

Fig. 18.22 (Continued)



(c)

Fig. 18.22 *(Continued)*

TABLE 18.7 Size of Gutters

PART A. I-P UNITS (showing permissible area of drainage, ft²)					
	Maximum Rainfall (in. per h)				
Diameter of Gutter (in.) 1⁄16 in./ft Slope	**2**	**3**	**4**	**5**	**6**
3	340	226	170	136	113
4	720	480	360	288	240
5	1250	834	625	500	416
6	1920	1280	960	768	640
7	2760	1840	1380	1100	918
8	3980	2655	1990	1590	1325
10	7200	4800	3600	2880	2400
	Maximum Rainfall (in. per h)				
Diameter of Gutter (in.) 1⁄8 in./ft Slope	**2**	**3**	**4**	**5**	**6**
3	480	320	240	192	160
4	1020	681	510	408	340
5	1760	1172	880	704	587
6	2720	1815	1360	1085	905
7	3900	2600	1950	1560	1300
8	5600	3740	2800	2240	1870
10	10,200	6800	5100	4080	3400

TABLE 18.7 Size of Gutters (*Continued*)

	Maximum Rainfall (in. per h)				
Diameter of Gutter (in.) ¼ in./ft Slope	**2**	**3**	**4**	**5**	**6**
3	680	454	340	272	226
4	1440	960	720	576	480
5	2500	1668	1250	1000	834
6	3840	2560	1920	1536	1280
7	5520	3680	2760	2205	1840
8	7960	5310	3980	3180	2655
10	14,400	9600	7200	5750	4800
	Maximum Rainfall (in. per h)				
Diameter of Gutter (in.) ½ in./ft Slope	**2**	**3**	**4**	**5**	**6**
3	960	640	480	384	320
4	2040	1360	1020	816	680
5	3540	2360	1770	1415	1180
6	5540	3695	2770	2220	1850
7	7800	5200	3900	3120	2600
8	11,200	7460	5600	4480	3730
10	20,000	13,330	10,000	8000	6660
PART B. SI UNITS (showing permissible area of drainage, m^2)					
	Maximum Rainfall (mm per h)				
Diameter of Gutter (mm) 5.2 mm/m Slope	**50.8**	**76.2**	**101.6**	**127.0**	**152.4**
76.2	31.6	21.0	15.8	12.6	10.5
101.6	66.9	44.6	33.4	26.8	22.3
127.0	116.1	77.5	58.1	46.5	38.7
152.4	178.4	119.1	89.2	71.4	59.5
177.8	256.4	170.9	128.2	102.2	85.3
203.2	369.7	246.7	184.9	147.7	123.1
254.0	668.9	445.9	334.4	267.6	223.0
	Maximum Rainfall (mm per h)				
Diameter of Gutter (mm) 10.4 mm/m Slope	**50.8**	**76.2**	**101.6**	**127.0**	**152.4**
76.2	44.6	29.7	22.3	17.8	14.9
101.6	94.8	63.3	47.4	37.9	31.6
127.0	163.5	108.9	81.8	65.4	54.5
152.4	252.7	168.6	126.3	100.8	84.1
177.8	362.3	241.5	181.2	144.9	120.8
203.2	520.2	347.5	260.1	208.1	173.7
254.0	947.6	631.7	473.8	379.0	315.9
	Maximum Rainfall (mm per h)				
Diameter of Gutter (mm) 20.9 mm/m Slope	**50.8**	**76.2**	**101.6**	**127.0**	**152.4**
76.2	63.2	42.2	31.6	25.3	21.0
101.6	133.8	89.2	66.9	53.5	44.6
127.0	232.3	155.0	116.1	92.9	77.5
152.4	356.7	237.8	178.4	142.7	118.9
177.8	512.8	341.9	256.4	204.9	170.9
203.2	739.5	493.3	369.4	295.4	246.7
254.0	133.8	891.8	668.9	534.2	445.9
	Maximum Rainfall (mm per h)				
Diameter of Gutter (mm) 41.7 mm/m Slope	**50.8**	**76.2**	**101.6**	**127.0**	**152.4**
76.2	89.2	59.5	44.6	35.7	29.7
101.6	189.5	126.3	94.8	75.8	63.2
127.0	328.9	219.2	164.4	131.5	109.6
152.4	514.7	343.2	257.3	206.2	171.9
177.8	724.6	483.1	362.3	289.9	241.4
203.2	1040.5	693.0	520.2	416.2	346.5
254.0	1858.0	1234.4	929.0	743.2	618.7

Source: Reprinted from the 2012 *International Plumbing Code*, © International Code Council (ICC), Washington, D.C. All rights reserved. www.iccsafe.org

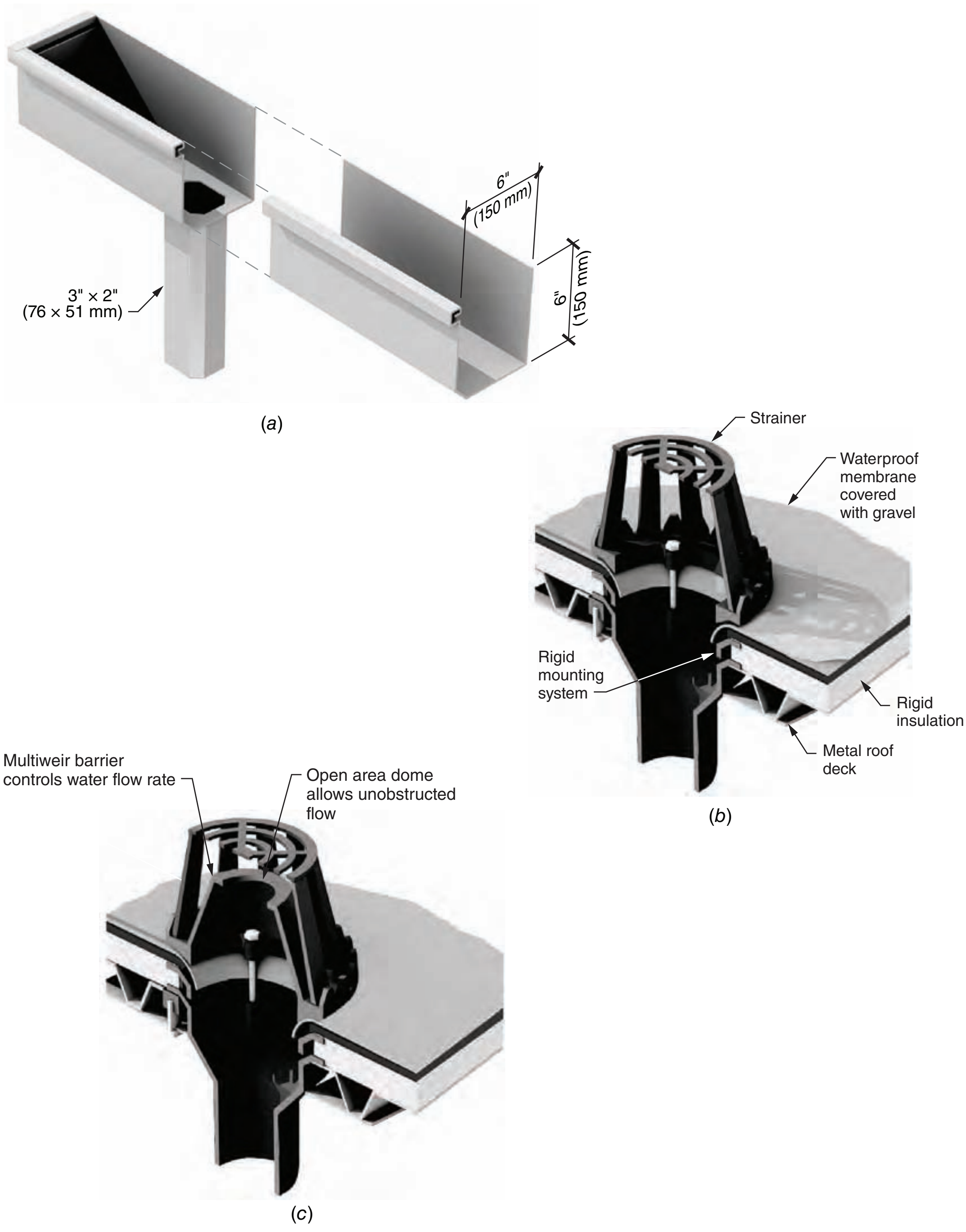


Fig. 18.23 *Storm drainage components. (a) Conventional gutter and leader for houses; sizes vary by manufacturer. (b) Ordinary roof drain (c) Roof drain for controlled flow.*

TABLE 18.8 Sizing Roof Drains, Leaders, and Vertical Rainwater Piping

PART A. I-P UNITS

Size of Drain, Leader, or Pipe (in.)	Flow (gpm)	*Maximum Allowable Horizontal Projected Roof Areas Square Feet at Various Rainfall Rates*					
		1 in./h	2 in./h	3 in./h	4 in./h	5 in./h	6 in./h
2	30	2880	1440	960	720	575	480
3	92	8800	4400	2930	2200	1760	1470
4	192	18400	9200	6130	4600	3680	3070
5	360	34600	17300	11530	8650	6920	5765
6	563	54000	27000	17995	13500	10800	9000
8	1208	116000	58000	38660	29000	23200	19315

PART B. SI UNITS

Size of Drain, Leader, or Pipe (mm)	Flow (L/s)	*Maximum Allowable Horizontal Projected Roof Areas Square Meters at Various Rainfall Rates*					
		25 mm/h	50 mm/h	75 mm/h	100 mm/h	125 mm/h	150 mm/h
50	1.8	268	134	89	67	53	45
75	5.52	818	409	272	204	164	137
100	11.52	1709	855	570	427	342	285
125	21.6	3214	1607	1071	804	643	536
150	33.78	5017	2508	1672	1254	1003	836
200	72.48	10776	5388	3592	2694	2155	1794

Source: © 2012 *Uniform Plumbing Code*; Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

NOTES: The sizing data for vertical conductors, leaders, and drains are based on the pipes flowing 7/24 full. For rainfall rates other than those listed, determine the allowable roof area by dividing the area given in the 1 inch/hour (25 mm/hour) column by the desired rainfall rate. Vertical piping may be round, square, or rectangular. Square pipe shall be sized to enclose its equivalent round pipe. Rectangular pipe shall have at least the same cross-sectional area as its equivalent round pipe, except that the ratio of its side dimensions shall not exceed 3 to 1.

Storm gutters and leaders can have an important impact on a building's appearance (Fig. 18.24). Alternatively, leaders can be set within buildings, and gutters can be built into a roof's surface to minimize the visual impact.

Fig. 18.24 The whimsical transformation of a custom designed rain gutter to an oversized spout serves as an architectural element at the Watering Can Theater at the Springs Preserve, Las Vegas. (© Alison Kwok; all rights reserved.)

Where routing of storm water inside a building is preferable, drains and leaders can be sized from Table 18.8, and horizontal piping can be sized from Table 18.9. Care should be taken to insulate such lines; cold rainwater inside pipes can cause condensation to form on the outside pipe surface, sometimes resulting in staining and other water damage.

EXAMPLE 18.3 Select the sizes for vertical conductors and horizontal storm drains for the building shown in Fig. 18.25. The roof, balcony, and courtyard areas are as shown, the rainfall rate is 4 in./h (100 mm/h), and the pitch of horizontal drains is ¼-in. slope per 1 ft of run (2%; approximately 20 mm/m).

SOLUTION

The sizes selected and shown in Fig. 18.25 may be verified in Tables 18.8 and 18.9. ■

TABLE 18.9 Sizing of Horizontal Rainwater Piping

PART A. I-P UNITS

Size of Pipe (in.)	Flow at ⅛ in./ft Slope (gpm)	Maximum Allowable Horizontal Projected Roof Areas Square Feet at Various Rainfall Rates					
		1 in./h	2 in./h	3 in./h	4 in./h	5 in./h	6 in./h
3	34	3288	1644	1096	822	657	548
4	78	7520	3760	2506	1880	1504	1253
5	139	13,360	6680	4453	3340	2672	2227
6	222	21,400	10,700	7133	5350	4280	3566
8	478	46,000	23,000	15,330	11,500	9200	7670
10	860	82,800	41,400	27,600	20,700	16,580	13,800
12	1384	133,200	66,600	44,400	33,300	26,650	22,200
15	2473	238,000	119,000	79,333	59,500	47,600	39,650

Size of Pipe (in.)	Flow at ¼ in./ft Slope (gpm)	Maximum Allowable Horizontal Projected Roof Areas Square Feet at Various Rainfall Rates					
		1 in./h	2 in./h	3 in./h	4 in./h	5 in./h	6 in./h
3	48	4640	2320	1546	1160	928	773
4	110	10,600	5300	3533	2650	2120	1766
5	196	18,880	9440	6293	4720	3776	3146
6	314	30,200	15,100	10,066	7550	6040	5033
8	677	65,200	32,600	21,733	16,300	13,040	10,866
10	1214	116,800	58,400	38,950	29,200	23,350	19,450
12	1953	188,000	94,000	62,600	47,000	37,600	31,350
15	3491	336,000	168,000	112,000	84,000	67,250	56,000

Size of Pipe (in.)	Flow at ½ in./ft Slope (gpm)	Maximum Allowable Horizontal Projected Roof Areas Square Feet at Various Rainfall Rates					
		1 in./h	2 in./h	3 in./h	4 in./h	5 in./h	6 in./h
3	68	6576	3288	2192	1644	1310	1096
4	156	15,040	7520	5010	3760	3010	2500
5	278	26,720	13,360	8900	6680	5320	4450
6	445	42,800	21,400	14,267	10,700	8580	7140
8	956	92,000	46,000	30,650	23,000	18,400	15,320
10	1721	165,600	82,800	55,200	41,400	33,150	27,600
12	2768	266,400	133,200	88,800	66,600	53,200	44,400
15	4946	476,000	238,000	158,700	119,000	95,200	79,300

PART B. SI UNITS

Size of Pipe (mm)	Flow at 10 mm/m Slope (L/s)	Maximum Allowable Horizontal Projected Roof Areas Square Meters at Various Rainfall Rates					
		25 mm/h	50 mm/h	75 mm/h	100 mm/h	125 mm/h	150 mm/h
75	2.1	305	153	102	76	61	51
100	4.9	700	350	233	175	140	116
125	8.8	1241	621	414	310	248	207
150	14.0	1988	994	663	497	398	331
200	30.2	4273	2137	1424	1068	855	713
250	54.3	7692	3846	2564	1923	1540	1282
300	87.3	12,375	6187	4125	3094	2476	2062
375	156.0	22,110	11,055	7370	5528	4422	3683

Size of Pipe (mm)	Flow at 20 mm/m Slope (L/s)	Maximum Allowable Horizontal Projected Roof Areas Square Meters at Various Rainfall Rates					
		25 mm/h	50 mm/h	75 mm/h	100 mm/h	125 mm/h	150 mm/h
75	3.0	431	216	144	108	86	72
100	6.9	985	492	328	246	197	164
125	12.4	1754	877	585	438	351	292
150	19.8	2806	1403	935	701	561	468
200	42.7	6057	3029	2019	1514	1211	1009
250	76.6	10,851	5425	3618	2713	2169	1807
300	123.2	17,465	8733	5816	4366	3493	2912
375	220.2	31,214	15,607	10,405	7804	6248	5202

TABLE 18.9 Sizing of Horizontal Rainwater Piping (*Continued*)

Size of Pipe (mm)	Flow at 40 mm/m Slope (L/s)	Maximum Allowable Horizontal Projected Roof Areas Square Meters at Various Rainfall Rates					
		25 mm/h	50 mm/h	75 mm/h	100 mm/h	125 mm/h	150 mm/h
75	4.3	611	305	204	153	122	102
100	9.8	1400	700	465	350	280	232
125	17.5	2482	1241	827	621	494	413
150	28.1	3976	1988	1325	994	797	663
200	60.3	8547	4273	2847	2137	1709	1423
250	108.6	15,390	7695	5128	3846	3080	2564
300	174.6	24,749	12,374	8250	6187	4942	4125
375	312.0	44,220	22,110	14,753	11,055	8853	7367

Source: ©2012 *Uniform Plumbing Code*; Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

NOTES: The sizing data for horizontal piping are based on the pipes flowing full. For rainfall rates other than those listed, determine the allowable roof area by dividing the area given in the 1 inch/hour (25 mm/hour) column by the desired rainfall rate.

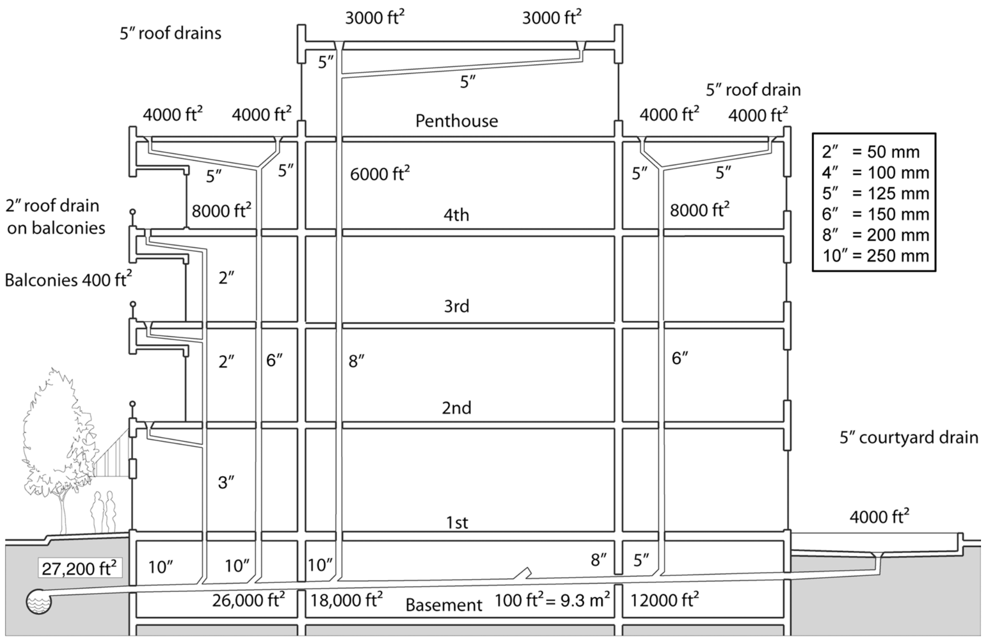


Fig. 18.25 *Separate storm drainage. Areas drained and corresponding sizes of vertical leaders and horizontal drains are from Tables 18.8 and 18.9. Storm drain piping within a building requires insulating covering with a vapor retarder on the outside. This prevents condensation (sweating) on the pipes when, in winter, warm, moisture-laden air in the building could reach the pipe surface (which would be cold from carrying icy water) and condense there—leading to wet, dripping conditions on the pipes. Each roof has two drains in case one is temporarily blocked. (Drawing by Nathan Majeski.)*

18.8 CASE STUDY— WATER AND BASIC DESIGN

Lady Bird Johnson Wildflower Center, Austin, Texas

Project Basics

- Location: Austin, Texas, USA
- Latitude: 30.18°N; longitude: 97.89°W; elevation: 621 ft (189 m) for Austin city
- Heating degree days: 1688 base 65°F (938 base 18.3°C); cooling degree days: 7171 base 50°F (3984 base 10°C); annual precipitation: 30 in. (762 mm) per year
- Building type: New construction; offices, visitor's center, classrooms
- Building area: 54,000 ft^2 (5017 m^2)
- Completed 1995
- Client: LBJ Wildflower Center
- Design team: Overland Partners and consultants

Background. The Lady Bird Johnson Wildflower Center is an award-winning project that exemplifies resource conservation through a careful union between the buildings and the surrounding landscape. Elements of the design process for water conservation and other strategies at the Wildflower Center are presented in the discussion that follows, in order to emphasize the importance of having an integrated design process when trying to achieve a wide array of goals—ranging from redeveloping the native landscape to showcasing the intrinsic beauty of local materials. In the case of the Wildflower Center, the client's values were important to the success of this project that aimed to manifest a 13-year campaign to bring research and resources together on behalf of native plants. It has become a place to learn about native plants and how to reduce water consumption while maintaining a beautiful outdoor habitat.

Initially named the National Wildflower Research Center, founded by Lady Bird Johnson and actress Helen Hayes in 1982, the Center has expanded beyond its original intentions to

Fig. 18.26 Lady Bird Johnson Wildflower Center in Austin, Texas; view to the Visitor's Center. (Photo by Jake Moore; © 2009 Alison Kwok; all rights reserved.)

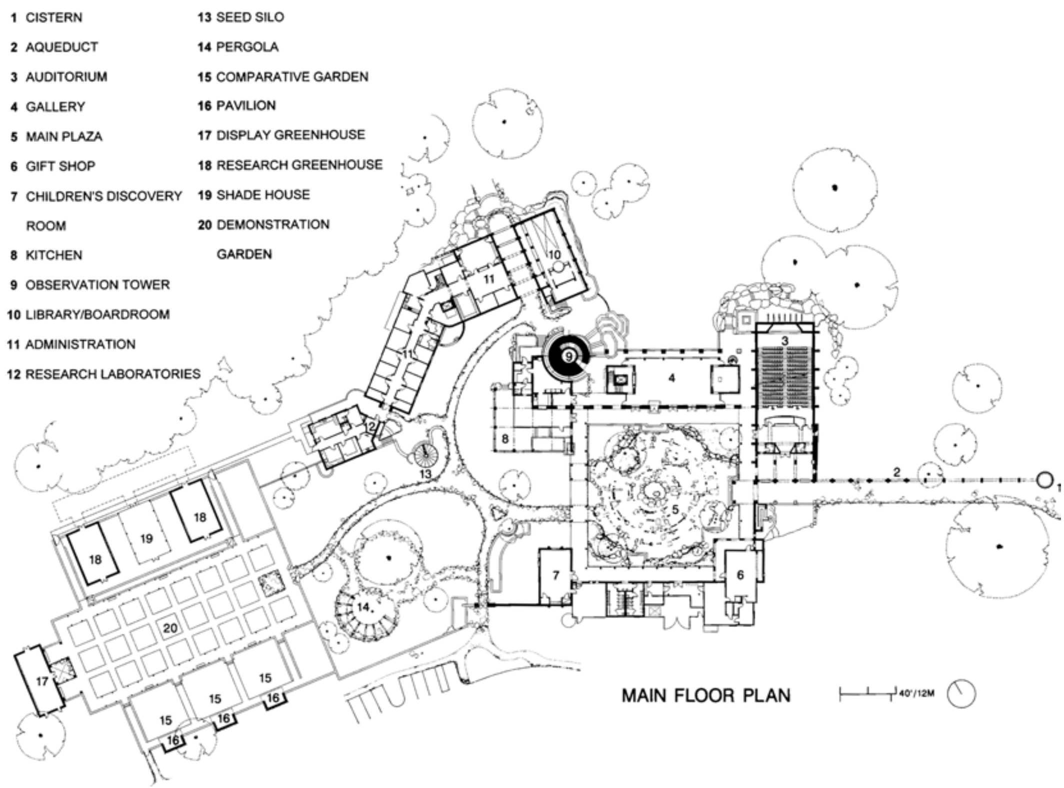


Fig. 18.27 *Site plan shows two cisterns, one at the far right (1), the other in the central observation tower (9). (© Overland Partners Architects; used with permission.)*

incorporate education, progressive environmental movements, and the publication of data on landscaping with native plants in the United States. To accommodate its success and growth, the Wildflower Research Center moved to a new site in 1995. In 2006, the Wildflower Center became an Organized Research Unit of The University of Texas at Austin's College of Natural Sciences and School of Architecture. Concern for water conservation led to many of the distinctive forms seen in the cisterns and waterways on the land. (The information that follows was provided by Overland Partners.)

Context. The Lady Bird Johnson Wildflower Center is a research center designed to share information with the public by increasing awareness, and understanding, of local native plants and landscapes. In 1997, the Center was renamed the Lady Bird Johnson Wildflower Center and its mission expanded to include educational opportunities for visitors. Within the last decade the Center has played an active role in land restoration, plant conservation, the Millennium Seed Bank Project, and the creation of the Sustainable Sites Initiative with the aid of the American Society of Landscape Architects.

Design Intent. The mission of the Wildflower Center is to: "increase the sustainable use and conservation of native wildflowers, plants and landscapes." Aligned with this, the design of the Center teaches by example with particular attention being given to the visitor's experience. Rather than creating one monolithic building, the project comprises several smaller buildings wrapped by landscaping, demonstration gardens, and a main

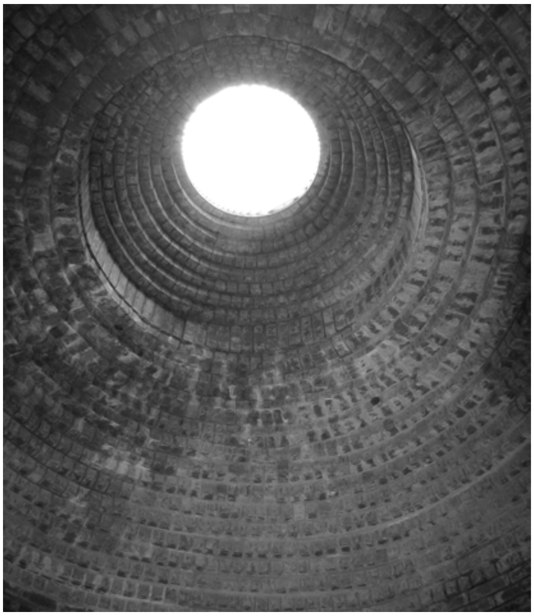


Fig. 18.28 *Oculus of the water tower cistern. The tower serves as a focal point for views of the site. (Photo by Jake Moore; © 2009 Alison Kwok; all rights reserved.)*

Fig. 18.29 *Entry cistern fed by aqueducts from the site's rainwater-harvesting system. (Photo © 2009 Alison Kwok; all rights reserved.)*

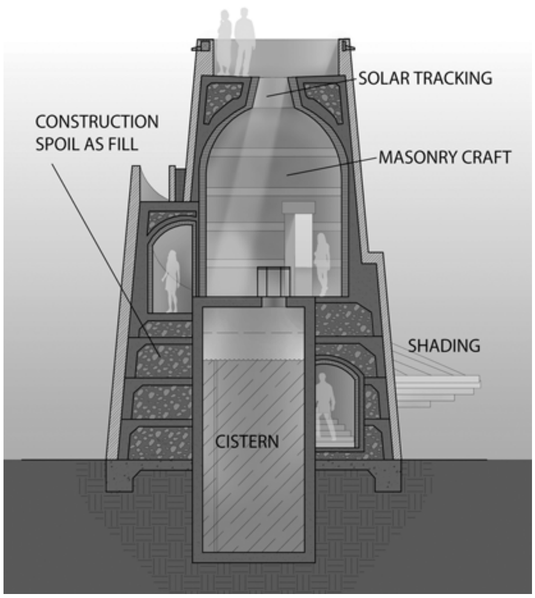


Fig. 18.30 *Section of the tower cistern (© Overland Partners Architects; used with permission.)*

Fig. 18.31 *Rainwater-harvesting system on local stone arches along the entry path surrounded by oak trees. (Photo © 2009 Alison Kwok; all rights reserved.)*

plaza. Framing views of the surrounding terrain, these buildings extend the notion that the Center is more about the landscape than the buildings. A key element of the design was to eliminate the need to pump water from the endangered Edwards Aquifer. Many of the native plants help conserve water, since they require only that supplied by available rainfall. Runoff from the building rooftops drains into various cisterns and storage tanks to be used later for irrigation. Some rooftops are connected with aqueducts that allow the water to flow to a shared storage tank/cistern.

The leading principles behind the design were as follows:

- The building and programs should support "total resource conservation."
- Respect existing native wildflowers, landscaping and plants.
- Harmonize built form with landscaping.
- Minimize the impact of the built environment.
- Enable visitor education through example.
- Eliminate the need to pump water from the endangered Edwards Aquifer.
- Respect and utilize the local vernacular, materiality, and craftsmanship.
- "Demonstrate an ecologically sensitive approach to the development of a site with fragile environmental conditions."
- Utilize and design sustainable technologies to aid in conservation efforts.

Design Criteria and Validation. The project was built in 1995, long before the Leadership in Energy and Environmental Design (LEED) certification process. In retrospect, the project complies with many of the principles that guide the LEED rating system. Sustainable design was desirable to maintain the Center's founding philosophies and the ethics of the design team, which were the driving forces behind the environmental design decisions. The intentions of the project were to demonstrate an ecologically sensitive approach to the development of a site with fragile environmental conditions, and to integrate the buildings and programs to support "total resource conservation," while showing the beauty of the native landscape and supporting over 400 native plant species.

Post-Occupancy Validation Methods. The success of the Lady Bird Johnson Wildflower Center resulted in more than 20 international, national, state, and local awards for its facilities, programs, and leadership in environmental design. It was calculated that the investment made in creating these facilities brought returns of more than $11 million in free media in the first two years. Based on the collected data, energy simulations were run using ENER-WIN—a software package used to analyze total building energy performance, developed in the Department of Architecture at Texas A&M University as part of the Vital Signs Curriculum Project. The overall energy performance of the building simulated by this software was calibrated to the actual building energy use based on utility bills for one year. The components of the energy usage were broken down and compared, to see the percent contribution to the HVAC load of the various design features—i.e., the use of daylighting strategies and a matching of HVAC and occupancy schedules.

Performance Data

- With an average rainfall of 30 in. (762 mm) per year, the whole rooftop system can collect approximately 300,000 gal (1,135,500 L) of rainwater per year.
- In total, the Center collects water from 17,000 ft^2 (1579 m^2) of roof space and can store more than 60,000 gal (227,100 L) in

Fig. 18.32 *Wood was reused from the site to create overhangs and trellises. (Photo by Jake Moore; © 2009 Alison Kwok; all rights reserved.)*

on-site cisterns and storage tanks, providing approximately 10–15% of the Center's yearly water needs for irrigation and landscaping.

- Approximately 10,600 gallons of water per inch of rain (1580 L/mm) are collected for the whole center.
- Five cisterns are used in total, with an approximate capacity of 65,000 gal (246,025 L): two cisterns at 20,000 gal (75,700 L) each, one at 5000 gal (18,925 L), the entry cistern at 12,000 gal (45,420 L), and the children's "little house" cistern holding 3000 gal (11,355 L).
- The entry collection cistern system is fed by 1167 ft^2 (108 m^2) of metal roof connected to a 12,000-gal (45,420-L) cistern. This cistern can collect 7000 gal per inch (1043 L/mm) of rain, or approximately 21,000 gal (79,485 L) per year.
- The children's area cistern collects water from 672 ft^2 (62 m^2) of roof, and has a 3000-gal (11,355-L) capacity. With approximately 420 gal per inch of rain (63 L/mm), it can collect 12,600 gal (47,691 L) of water per year.
- All cisterns are located aboveground except for the transfer station, which is underground.
- Recycled materials included wood flooring and on-site non-biodegradable construction spoil used to fill the tower structure. Local stone, wood flooring, and site boulders were obtained from within a 150-mile (241-km) radius from site.

The project received the following awards and citations:

1995:

Texas Society of Architects – Honor Award

Austin Commercial Real Estate Society – Good Egg Award

Associated Builders and Contractors Awards – First Place for Excellence in Construction

1996:

Recycling and Education Awareness Citations by Keep Austin Beautiful

Good Steward Award by the National Arbor Foundation

American Society of Landscape Architects – San Antonio Design Honor Award

American Society of Landscape Architects – State of Texas Design Honor Award

American Society of Landscape Architects – National Design Honor Award

Associated General Contractors – San Antonio Design Honor Award

Associated General Contractors – Regional Honor Award

Associated General Contractors – Dallas Chapter Summit Award

Associated General Contractors – National Design Honor Award

American Institute of Architects – San Antonio chapter Design Honor Award

1998:

Business Week/Architectural Record – Award Semi-finalist

2000:

American Institute of Architects Committee on the Environment – Earth Day 2000 Top Ten

FOR FURTHER INFORMATION

Overland Partners Architects: http://www.overlandpartners.com/

Lady Bird Johnson Wildflower Center: http://www.wildflower.org/

Rocky Mountain Institute, *Green Developments CD*, version 2.0, 2001

References and Resources

Brown, G. Z., J. Reynolds, and S. Ubbelohde. 1982. *InsideOut: Design Procedures for Passive Environmental Technologies.* John Wiley & Sons. Hoboken, NJ.

Corbett, M. 1981. *A Better Place to Live.* Rodale Press. Emmaus, PA.

Ferguson, B. 1998. *Introduction to Stormwater.* John Wiley & Sons. Hoboken, NJ.

Gleick, P. 1998. *The World's Water*. Island Press, Washington, DC.

International Association of Plumbing and Mechanical Officials. 2012. *Uniform Plumbing Code*. Walnut, CA.

International Code Council. 2012. *International Plumbing Code*. ICC. Washington, DC.

McPherson, E. G. (ed.). 1984. *Energy-Conserving Site Design*. American Society of Landscape Architects. Washington, DC.

Milne, M. 1976. *Residential Water Conservation*. U.S. Office of Water Research and Technology, Department of Commerce, NTIS. Springfield, VA.

U.S. Environmental Protection Agency. 1975. *Manual of Individual Water Supply Systems*. Washington, DC.

U.S. Geological Survey, Water Resources of the United States. http://water.usgs.gov/

CHAPTER 19

Water Supply

WITH WATER, ONE OF THE DESIGNER'S FIRST concerns is to match the quality of the water to the task it performs. As this becomes a more serious design issue, designers will provide for the recycling of water within and around buildings, as well as specify plumbing fixtures that use less water. Table 19.1 shows typical relationships between water quality and usage. Water recycling and conservation are discussed in detail in Chapter 20. In this chapter we deal primarily with *potable* (drinkable) water: first with issues of water quality and then with the matter of ensuring an adequate supply of water throughout a building.

19.1 WATER QUALITY

A summary of water quality at the various stages of the hydrologic cycle was shown in Fig. 18.4. As precipitation, water contains few impurities: Almost no bacterial content is present, and only small amounts of minerals and gases can be expected. Surfaces are needed to collect this nearly pure water—and from these surfaces, foreign substances can readily contaminate the water. These pollutants can affect water's physical (mostly organic), chemical (mostly inorganic), biological, or radiological characteristics. Both surface water and groundwater are subject to pollution.

The U.S. National Drinking Water Clearinghouse is a source of information on water supply and wastewater treatment systems. Its brief history of waterborne diseases worldwide begins with a major cholera epidemic that began in Calcutta, India, in 1817, killing thousands and spreading by 1832 to New York City, emptying the streets in panic over the disease. In 1854, a London physician demonstrated that local cases of cholera could be traced to one pump contaminated with sewage from a nearby house, but how the disease was transmitted remained a mystery. In summer 1859, London's Thames River, carrying combined storm and sanitary wastes, stank so badly that Parliament was suspended. In 1892, the bacterium causing cholera was identified during an epidemic in Hamburg, Germany, proving the relationship between contaminated water and the disease. In 1939, an outbreak of typhoid fever killed 60 people at an Illinois mental hospital; typhoid and gastroenteritis resulted from an accidental pumping of polluted river water into supply mains in Rochester, New York, in 1940. Another worldwide cholera epidemic began in Indonesia in 1961, eventually reaching Latin America by 1991. In 1993, an outbreak of cryptosporidiosis in the public water supply of Milwaukee, Wisconsin, shook the public's faith in water systems across the United States; that outbreak killed 104 and infected more than 400,000 people.

In response to this history, we disinfect huge quantities of water, expending energy and adding chemicals so that every drop of water entering North American buildings is potable. Again, the

TABLE 19.1 Water Use and Quality in Buildings

Use	Desired Quality
A. CONSUMED	
1. Drinking and cooking	Potable
2. Bathing	Potable
3. Laundering	Soft
4. Irrigation and watering of livestock	Unpolluted
5. Industrial processes	As required
6. Vapor to increase the relative humidity of air	
B. CIRCULATED	
1. Hot water for heating	*Note:* Makeup water should be soft or neutral and, for swimming, potable
2. Chilled water for cooling	
3. Condenser cooling water	
4. Swimming pool water	
5. Steam for heating, later condensed	
C. GENERALLY STATIC	
1. Water stored for fire protection	
2. Water in fire standpipes	
3. Water in sprinkler piping	
D. CONTROLLED	
1. Vapor condensed to reduce relative humidity of air	

Note: For water uses in Section A, flow is often continuous. Section B comprises uses for which flow other than circulation is intermittent or at a relatively low rate, the water added to the systems being known as *makeup water.* Items C2 and C3 call for piping to provide adequate, though infrequent, flow in emergencies. Item D1 relates only to moisture condensed out of the air and involves no design for supply.

high-grade resource/low-grade use question arises; recycled water for lower-grade use is discussed in Chapter 20.

(a) Physical Characteristics

Some of the most noticeable aspects of water quality fall within this category. Water from surface sources (roof runoff, streams, rivers, lakes, ponds) is particularly subject to physical pollutants.

Turbidity is easy to see and thus is a likely source of dissatisfaction for the would-be consumer. It is caused by the presence of suspended material such as clay, silt, other inorganic material, plankton, or finely divided organic material. Even those materials that do not adversely affect health are usually aesthetically objectionable.

Color, another visible alteration, is often caused by dissolved organic matter, as from decaying vegetation. Some inorganic materials also color water, as do microorganisms. Like turbidity, such color changes usually do not threaten health, but they are often psychologically undesirable.

Taste and *odor* can be caused by organic compounds, inorganic salts, or dissolved gases. This condition can be treated only after a chemical analysis has identified which source is responsible.

Temperature is another characteristic of psychological importance—we expect drinking water to be cool. In general, water supplied between 50°F and 60°F (10°C and 16°C) is preferred.

Foamability is usually caused by concentrations of detergents. The foam itself does not pose a serious health threat, but it may indicate that other, more dangerous pollutants associated with domestic waste are also present. Because of increased foaming in water in the 1960s, today's detergents must use linear alkylate sulfonate (LAS), which biodegrades rapidly—except in the absence of oxygen. Because this lack of oxygen is characteristic of some septic tank drainage fields, foam in drinking water should be investigated promptly.

(b) Chemical Characteristics

Groundwater is particularly subject to chemical alteration because as it moves downward from the surface it slowly dissolves some minerals contained in rocks and soils. A chemical analysis (such as that given in Table 19.2) is usually required for individual water supply sources. Such analysis will indicate: (1) the possible presence of harmful or objectionable substances, (2) the potential for corrosion within the water supply system, and (3) the tendency for the water to stain fixtures and clothing. Concentrations are expressed in milligrams per liter (mg/L), which is essentially equivalent to parts per million (ppm).

Some general terms commonly used to describe chemical characteristics of water are as follows:

Alkalinity. Caused by bicarbonate, carbonate, or hydroxide components. Testing for these components of water's alkalinity is a key to determining which treatments to use.

Hardness. A relative term (see Fig. 19.1). Hard water inhibits the cleaning action of soaps and detergents, and it deposits scale on the inside of hot water pipes and cooking utensils, thus wasting heating fuel and making utensils unusable. Hardness, which is caused by calcium and

TABLE 19.2 Example of Chemical Analysis of Water

Quality		Parts per Million (ppm)[a]
Total hardness	$CaCO_3$	30
Calcium hardness	$CaCO_3$	20
Alkalinity (methyl orange)	$CaCO_3$	27
Alkalinity (phenolphthalein)	$CaCO_3$	0
Free carbon dioxide	CO_2	13.5
Chlorides	Cl	6
Sulfates	SO_4	4
Silica	SiO_2	19
Phosphates—normal	PO_4	0
Phosphates—total	PO_4	0.5
Iron—total	Fe	1.6
Total dissolved solids		66
Turbidity or sediment		Present

Source: A report by Olin Water Service for a private well in Virginia.

[a]Note that ppm and mg/L are essentially equivalent terms for concentration in water.

magnesium salts, can be classified as temporary (carbonate) or permanent (noncarbonate). Temporary hardness is largely removed when the water is heated—it forms the scale just described. Permanent hardness cannot be removed by simple heating (see Section 19.4*c*).

pH. A measure of the water's hydrogen ion concentration, as well as its relative acidity or alkalinity (Fig. 19.1). A pH of 7 is neutral. Measurements below 7 indicate increasing acidity (and corrosiveness); water in its natural state can have a pH as low as 5.5, with 0 being the ultimate acidity. Measurements higher than 7 indicate increasing alkalinity. A pH as high as 9 can be found in water in its natural state, with 14 representing the ultimate alkalinity. The pH value is the starting point for determining treatments for corrosion control, chemical dosages, and disinfection.

Unintentional chemical additions to water supplies most commonly include the following elements:

Toxic substances are occasionally present in water supplies. Local health authorities can provide information about acceptable concentrations of such substances as arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr^{6+}), cyanides (CN), fluoride (F), lead (Pb), selenium (Se), and silver (Ag). Although limited amounts of *fluoride* are frequently added to water supplies to help prevent tooth decay, fluorides in excess of such optimum concentrations can produce mottling of teeth. *Lead* poses a dangerous threat, even in relatively small amounts, because it is a cumulative poison. Lead in water usually comes from lead piping (in older buildings or cities) or from corrosive water on lead-painted roofs. The maximum recommended concentration is 0.05 mg/L.

Unfortunately, the list of toxic chemicals is expanding, and as chemical waste dumps have been abandoned or mismanaged, groundwater

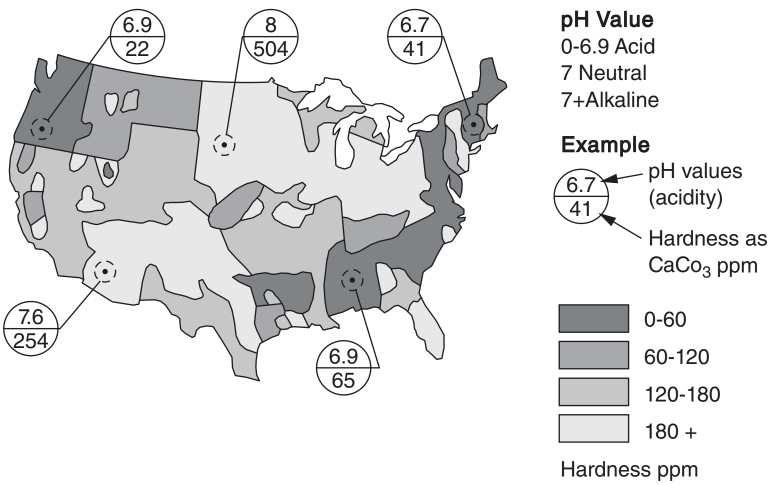


Fig. 19.1 *Approximate groundwater chemical characteristics across the United States. Treatment may be needed when the pH is less than 7.0 (acidity results in corrosion) or when hardness as $CaCO_3$ exceeds 65 ppm (ppm and mg/L are essentially identical measures). (Courtesy of Progressive Architecture.)*

has become contaminated. The U.S. Environmental Protection Agency (EPA) has estimated that 75% of both active and abandoned chemical waste dumps—some 51,000 in all—are leaking. In addition to the following list of inorganic chemicals, we are becoming aware of many new organic chemicals as well, some of which are suspected of causing 5% to 20% of U.S. cancers. The threat to our groundwater supplies is illustrated in Fig. 19.2. Once polluted, aquifers are extremely difficult to clean. This is one reason why ground-source heat pumps are tightly regulated.

Chlorides can enter water as it passes through geologic deposits formed by marine sediment, or because of pollution from seawater, brine, or industrial or domestic wastes. A noticeable taste results from chloride in excess of 250 mg/L.

Copper can enter water from natural copper deposits or from copper piping that contains corrosive water. Concentrations of copper in excess of 1.0 mg/L can produce an undesirable taste.

Iron is frequently present in groundwater. Corrosive water in iron pipes will also add iron to water. At concentrations above 0.3 mg/L, iron can lend a brownish color to washed clothes and can affect the taste of the water.

Manganese can both pose a physiological threat (it is a natural laxative) and produce color and taste effects similar to those produced by iron. The recommended limit is 0.05 mg/L.

Nitrates in high concentrations pose a threat to infants, in whom they can cause "blue baby" disease. In shallow wells, nitrate concentrations can indicate seepage from deposits of livestock manure.

Pesticides, a growing threat to water supplies, are particularly common in wells near homes that have been treated for termite control. Avoid using pesticides near wells.

Sodium is primarily dangerous for people with heart, kidney, or circulatory ailments. For a low-sodium diet, the sodium in drinking water should not exceed 20 mg/L. Salts spread on roadways for ice control can leach into the soil and enter groundwater. Note that some water softeners (discussed in Section 19.4*c*) can raise sodium concentrations in water.

Sulfates, which have laxative effects, can enter groundwater from natural deposits of Epsom salts (magnesium sulfate) or Glauber's salt (sodium sulfate). Concentrations should not exceed 250 mg/L.

Zinc sometimes enters groundwater in areas where it is found in abundance. Although not a health threat, it can cause an undesirable taste at concentrations above 5 mg/L.

(c) Biological Characteristics

Potable water should be kept as free as possible of disease-producing organisms—bacteria, protozoa,

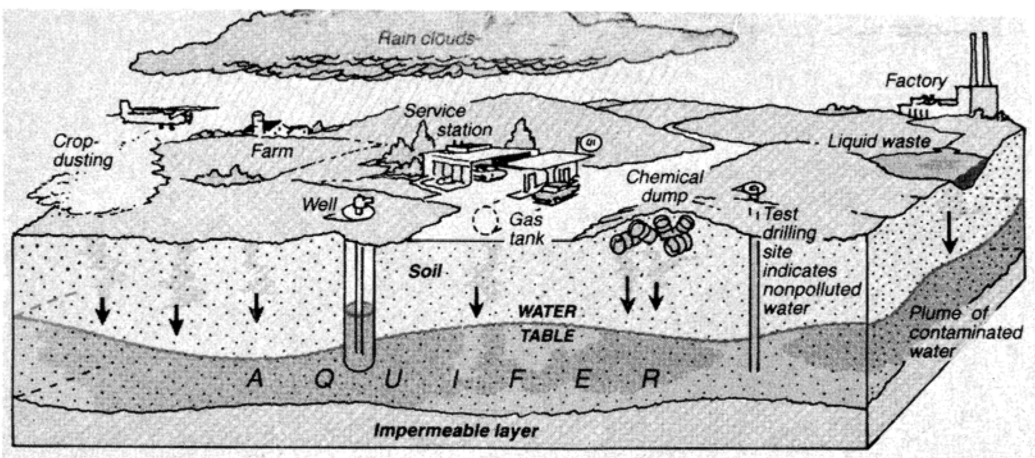


Fig. 19.2 *How groundwater becomes contaminated. The "plume" formed by contaminants can often go undetected. (© 1982 by Newsweek, Inc.; all rights reserved. Reprinted by permission.)*

and viruses. These organisms are not easily identified; a thorough biological water test is complex and time-consuming. For this reason, the standard test is for *one* kind of bacteria—the coliform group (*Escherichia coli*, better known as *E. coli*), which is always present in the fecal wastes of human beings (as well as those of many animals and birds) and which outnumbers all other disease-producing organisms in water. The recommended maximum concentration of coliform bacteria is one organism per 100 mL (about ½ cup) water.

For biological activity to be kept to a minimum in drinking water, a water source should be chosen that does not normally support much plant or animal life—hence the popularity of groundwater rather than surface water as a source. In addition, the supply should be protected from subsequent biological contamination. Where cities depend on small lakes for water, human beings are frequently excluded from the watersheds. Organic fertilizers and nutrient minerals should also be kept out of the water supply to further discourage biological activity. For the same reason, stored water should be kept dark and at low temperatures. Finally, organisms (or their by-products) are commonly destroyed at treatment facilities.

(d) Radiological Characteristics

The mining of radioactive materials and the use of such materials in industry and power plants have produced radiological pollution in some water supplies. Because radiological effects are cumulative, concentrations of radioactive materials should be low. "Safe" minimum concentrations have continually been revised downward for other radiation exposures; it is advised to consult the local public health service for current recommendations.

19.2 FILTRATION

In the preceding section, water pollution was broken down into physical, chemical, biological, and radiological categories. The various forms of treatment for such pollutants do not necessarily fall into the same categories, as one treatment may be effective for several different polluted conditions. A general look at common domestic water quality problems and treatments is provided in Table 19.3.

We begin with filtration, because so often it is the first treatment in a series; it is also one of the oldest and simplest methods. This very common treatment removes suspended particles, some bacteria, and color or taste by passing water through a permeable fabric or a porous bed of materials. The more common approaches are listed in the following subsections, beginning with filtering to remove suspended particles, and then moving on to more specialized applications for the removal of iron and/or manganese, tastes, and odors.

(a) Sedimentation

Before water enters a filter, this process removes some suspended matter simply by allowing time,

TABLE 19.3 Common Water Quality Problems and Treatment in Small Systems

Item	Cause	Bad Effect	Correction
Hardness	Calcium and magnesium salts from underground flow	Clogging of pipes by scale, burning out of boilers, and impaired laundering and food preparation	Ion-exchanger (zeolite process)
Corrosion	Acidity, entrained oxygen and carbon dioxide (low pH)	Closing of iron pipe by rust, leaking connections, destruction of brass pipe	Raising the alkaline content (neutralizer)
Biological pollution	Contamination by organic matter or sewage	Disease	Chlorination by sodium hypochlorite or chlorine gas; or ozonation
Color	Iron and manganese	Discoloration of fixtures and laundry	Chlorination or ozonation and fine filtration
Taste and odor[a]	Organic matter	Unpleasantness	Filtration through activated carbon (purifier); aeration
Turbidity[a]	Silt or suspended matter picked up in surface or near-surface flow	Unpleasantness	Filtration

[a]These problems are not common in private systems that use deep wells.

the inactivity of the water, and gravity to do the work of settling out heavier suspended particles. Simple basins, ponds, or tanks constructed for this purpose are large enough to retain the water for at least 24 hours and are equipped with baffles to slow the water flow. To clean out the sediment, water usually is diverted to an identical second basin while the first is being cleaned.

(b) Coagulation

This process also removes suspended matter, along with some coloration. A chemical such as *alum* (hydrated aluminum sulfate) is added to water made turbulent by baffles or static mixers to distribute the chemicals evenly.

(c) Flocculation

The water is then held in a quiet condition in which the suspended particles will combine with the alum to form *floc*. These heavy particles then settle out in a process similar to sedimentation. Some adjustment of the pH may be necessary.

See the National Drinking Water Clearinghouse *Tech Brief* (September 1996), *Filtration*, for details on the following methods of filtering.

(d) Slow Sand Filters

These are common in small-scale water supply systems (Fig. 19.3; also see Fig. 18.8 for a rainwater application). Not suitable for water with high turbidity, they do not usually require coagulation/flocculation and may not even require sedimentation. Water should not be chlorinated before entering this filter, because it will interfere with the subsequent biological activity. These filters are able to remove up to 99.9% of *Giardia* cysts.

Slow sand filters are low-maintenance, easily constructed devices that should be cleaned as often as the turbidity of the water demands—from once a day to perhaps once a month. They are cleaned by removal and replacement of about the top 1 in. (25 mm) of sand, which has formed a layer of biological slime called (descriptively) the *schmutzdecke*, which traps small particles and degrades organic material in the water. This sand is then either washed for reuse or discarded.

The approximate rate of flow is slow, requiring a rather large surface area: 0.03 to 0.10 gpm per ft^2 (0.02 to 0.07 L/s per m^2) of filter bed surface; in other units, 40 to 140 gal per day per ft^2 (1630 to 5720 L per day per m^2) of filter bed surface. Overall thickness is usually 30 in. to 48 in. (762 mm to

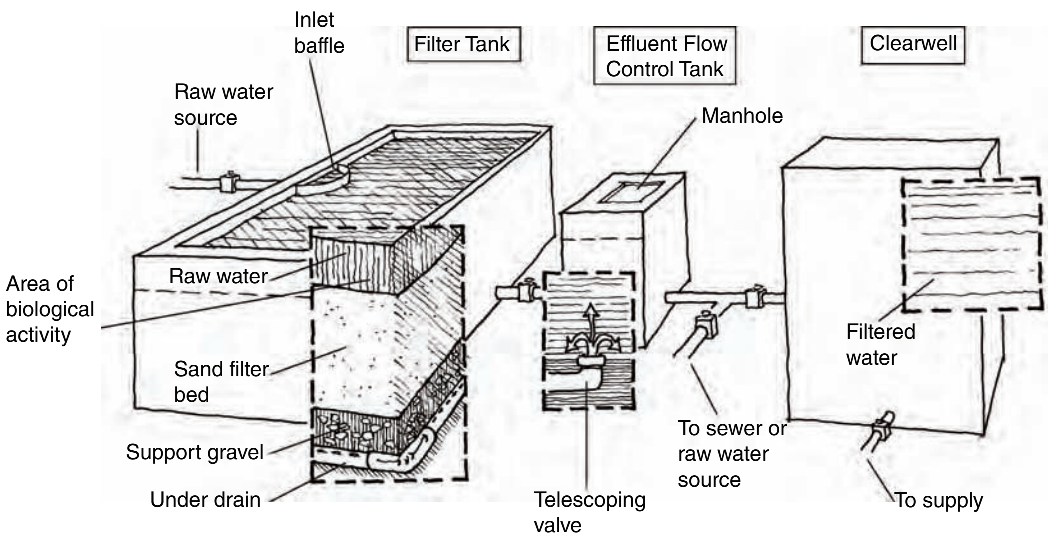


Fig. 19.3 Slow sand filter effective in removing cysts of Giardia. *Water should not be chlorinated before it enters the filter. From National Drinking Water Clearinghouse.* Tech Brief *(September 1996),* Filtration. *U.S. Environmental Protection Agency. Washington, DC. Redrawn by Dain Carlson.*

1219 mm) of sand over 12 in. (304 mm) of gravel with an underdrain system.

In freezing temperatures, slow sand filters must be housed; if they develop an ice layer, this prevents cleaning.

(e) Diatomaceous Earth Filters

Also known as *precoat* or *diatomite filters*, these can be of either the vacuum or the pressure type. They rely on a layer of diatomaceous earth—a minimum of $\frac{1}{8}$-in. (3-mm) thick layer, placed on a septum or filter element (for *Giardia* removal, the thickness should be increased to about $\frac{1}{5}$ in. [5 mm]). They are most suitable for water with low bacterial counts and low turbidity. Simple to operate and effective in removing cysts, algae, and asbestos, they require periodic attention to remain effective, including backwashing every 1 to 4 days.

(f) Direct Filtration

Intended for water supplies of high quality and seasonally consistent flow, these systems omit sedimentation but should include coagulation for most effective *Giardia* removal. These are often used with steel pressure tanks to maintain pressure in the water supply line.

Packaged filtration combines features such as chemical addition, flocculation, and sedimentation, along with filtration, in one compact unit. Most often used for small community water supplies, these systems treat surface water to remove turbidity, color, and coliform organisms.

(g) Membrane Filtration

Also called *microfiltration* or *ultrafiltration*, this rapidly developing technique can remove bacteria, *Giardia*, and some viruses. It does not require coagulation as pretreatment. Using hollow fiber or spiral-wrapped membranes, it is able to exclude all particles greater than 0.2 micron from the water stream. It is best used on water supplies of low turbidity because of fouling of the fibers or membranes.

Water is forced at high pressure through these filters. The contaminants trapped on the inflow side must be frequently removed by reversing the flow and flushing the waste; calcium and other persistent contaminants must be periodically removed with chemical cleaning.

Nanofiltration, using much smaller pores, is discussed in Section 19.3.

(h) Cartridge Filtration

Increasingly popular on lavatory faucets as well as on small supply systems, these systems are easy to operate and maintain. They require water of low turbidity and last longer when some prefiltering by more crude means is performed upstream. They can exclude particles of 0.2 micron (or even smaller). A disinfectant can prevent surface-fouling microbial growth on the cartridge filters; some periodic chemical cleaning will likely be required.

(i) Other Filters

Activated carbon filters are particularly effective for removing tastes and odors. The water is passed through granular carbon, which attracts large quantities of dissolved gases, soluble organics, and fine solids.

Porous stone, *ceramic*, or *unglazed porcelain filters* (also called *Pasteur filters*) are usually made in small sizes so that they can be attached to water faucets. They are used widely in some countries, such as Mexico, but poor maintenance or hairline cracks often lead to bacterial infiltration, complicating the filtration process. A more positive approach to the disinfection of drinking water thus is desirable.

19.3 DISINFECTION

Disinfection is the most important health-related water treatment, because it destroys microorganisms that can cause disease in human beings. Disinfection is required of water supply systems that rely on surface water or groundwater sources under the influence of surface water. Initially, primary disinfection achieves the desired level of microorganism kill (inactivation); then secondary disinfection maintains a disinfectant residual in the treated water that prevents microorganism regrowth.

Although chlorination has become the standard approach to removing harmful organisms from water, there are alternatives: nanofiltration, ultraviolet (UV) radiation (unsuitable for water with high turbidity because it cannot easily penetrate), bromine, iodine, ozone, and heat treatment, among others. Chlorine continues to disinfect after the initial application. It is this continuing secondary disinfection that has made it universally relied on, despite dangers such as that posed by deadly chlorine gas. Although chlorine affects the taste and odor of water, it is also effective in removing less desirable tastes and odors. Unfortunately, chlorine can react with organic materials in water to form halogenated by-products. It is easier to either remove the organic materials before treatment, or to use another disinfectant strategy, than to try to remove these halogenated by-products after chlorine treatment.

See the National Drinking Water Clearinghouse *Tech Brief* (June 1996), *Disinfection*, for details on the methods presented in Subsections 19.3(a) through 19.3(d).

(a) Chlorination

Factors that affect chlorine's ability to disinfect include:

1. *Chlorine concentration.* The higher the concentration, the faster and more complete the rate of disinfection.
2. *Contact time.* The longer the chlorine contacts the organisms in water, the more complete the disinfection. At a minimum, 0.4 mg/L of chlorine should contact water 30 minutes before use.
3. *Water temperature.* The higher the temperature during contact, the more complete the disinfection.
4. *pH.* The lower the pH, the more effective the disinfection.

There are three common forms in which chlorine is used to disinfect water supplies. *Chlorine gas* is stored in a cylinder (Fig. 19.4) as a liquid under high pressure and is released (as a gas) by a regulator to

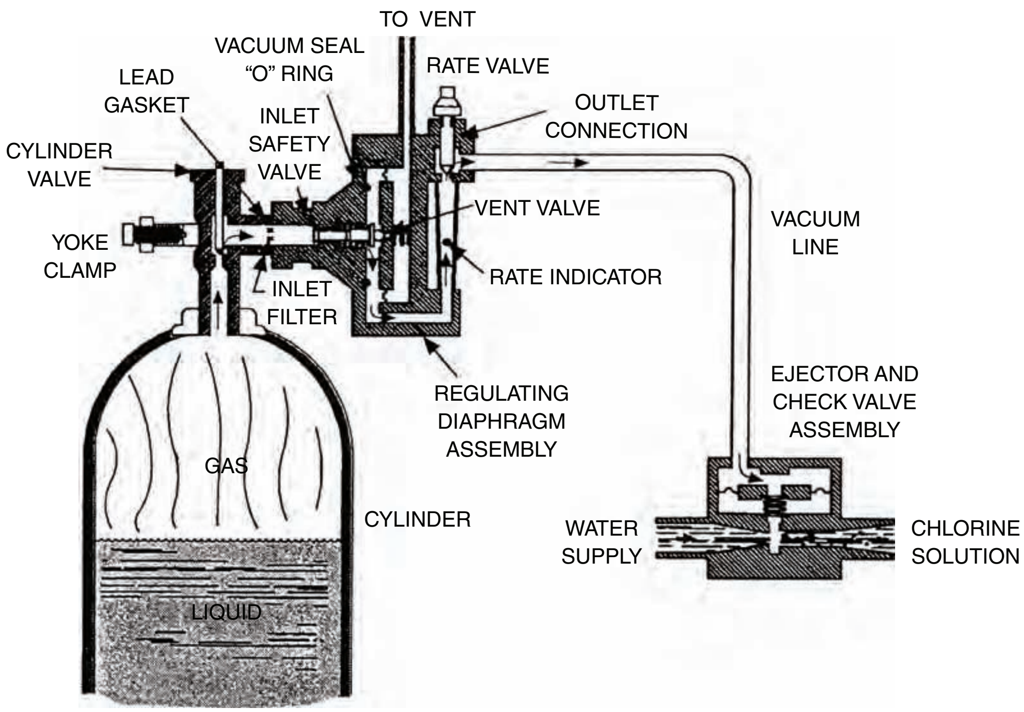


Fig. 19.4 *Cylinder-mounted chlorinator for automatic disinfection of supply water. From National Drinking Water Clearinghouse.* Tech Brief *(June 1996),* Disinfection*. U.S. Environmental Protection Agency. Washington, DC.*

an injector attached to a water pipe or tank. The injector passes highly pressurized water through a venturi orifice, creating a vacuum that draws the chlorine into the water stream.

Sodium hypochlorite solution is easier to handle than deadly chlorine gas but is very corrosive and decomposes rather quickly. It should be stored in a cool, dark, dry area for no more than a month. *Hypochlorinators* automatically pump (or inject) a sodium hypochlorite solution into water. They are usually no larger than the pumps used in small water systems. Some hypochlorinators are specially designed for low and fluctuating water pressures or for use where electricity is not available.

Solid calcium hypochlorite is a white solid containing 65% available chlorine that dissolves easily in water. It is corrosive, with a strong odor, but very stable and can be stored for up to a year. However, it readily absorbs moisture, forming chlorine gas; also, reactions between calcium hypochlorite and organic materials (wood, cloth, petroleum products) can generate enough heat to cause a fire or explosion. Again, hypochlorinators are used to deliver the disinfectant to water.

(b) Chloramine

This is generated on site by adding ammonia to water containing chlorine or when water containing ammonia is chlorinated. This is a weaker disinfectant against viruses or protozoa than the chlorination processes, but it produces fewer disinfection by-products. It is most often used as a secondary rather than a primary disinfectant. Again, hypochlorinators are used to inject chlorine, after which ammonia is added.

(c) Ozonation

This was first used in full-scale drinking water treatment in 1906. It is a powerful oxidizing and disinfecting agent, destroying most bacteria, viruses, and other pathogenic organisms. It requires a shorter contact time and dosage than chlorine and leaves no chlorine taste. Ozone is formed by passing dry air (or pure oxygen) through a system of high-voltage electrodes. It is an unstable gas and must be generated on site. When ozone reacts with an organic, it produces oxygen and an oxidized form of the organic. Ozone not used in this process quickly decays to oxygen.

In the United States, ozone is commonly used in cooling tower water treatment (Fig. 19.5), where its effectiveness against *Legionella pneumophila* is especially appreciated, as well as its control of algae and scale that can greatly reduce cooling efficiency. Ozone is also used in food processing, wastewater cleanup, smoke removal, swimming pools and spas, bottled water, and pulp and paper bleaching.

Equipment includes an ozone generator, a contactor, and a destruction unit, plus instrumentation and controls. Operation and maintenance are relatively complex; electricity accounts for 26% to 43% of the operating costs for small systems. Because it acts only as a primary disinfectant, a secondary disinfectant (often chlorine) is usually required.

(d) Ultraviolet Radiation

Special lamps are used within a reactor (Fig. 19.6), whose radiation disrupts the genetic material of the cells of organisms, making them unable to reproduce. Effective against bacteria and viruses, UV radiation is known to inactivate *Giardia* or *Cryptosporidium* cysts. UV radiation is an effective primary disinfectant system, requiring a short contact time and without halogenated by-products. Yet again, a secondary disinfectant system is usually necessary. This system is not suitable for water that contains high levels of suspended solids, turbidity, color, or soluble organic matter.

(e) Nanofiltration

These filter membranes start with pore sizes of 0.2 to 0.3 micron and are then dipped into a polymer that leaves a thin film, decreasing the pore size to 1 nanometer. This pore size removes bacteria, viruses, pesticides, and organic material. It also gives the membranes an affinity for calcium, contributing to water softening. However, it also means that the membranes need periodic acid cleaning to remove the calcium deposits. Adding phosphates to nanofiltered water reduces its capacity to dissolve lead.

With such extremely small pore sizes, this process requires very high water pressures, in turn requiring energy. Yet again, a secondary disinfectant system is usually necessary.

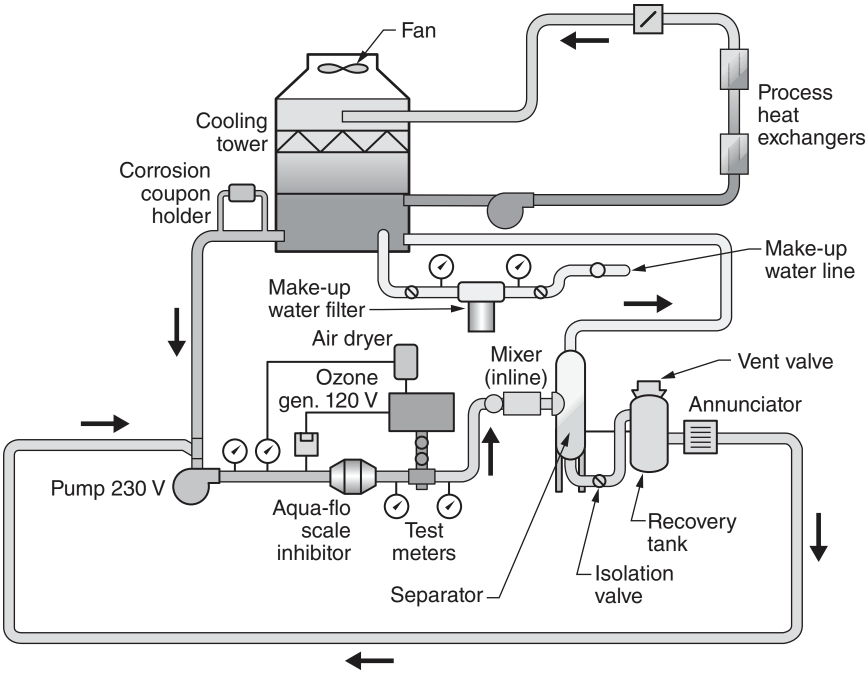


Fig. 19.5 *Recycled cooling tower water is treated by an ozonator, a magnetic descaler, and a filtration system. This controls scale formation, algae and slime, corrosion, and sludge buildup. (Courtesy of Aqua-Flo, Inc., Baltimore.)*

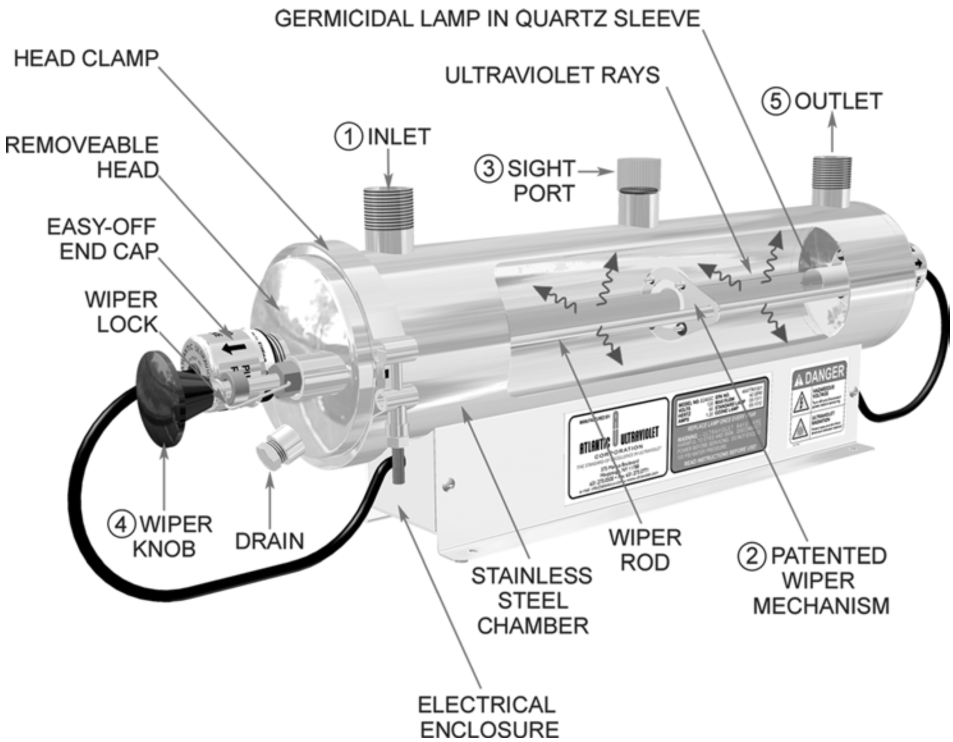


Fig. 19.6 *Ultraviolet lamps in water purifiers eradicate harmful microorganisms. The dispersion of short radiation waves makes the water suitable for even the most stringent consumers, including hospitals, laboratories, and pharmaceutical manufacturing. (Courtesy of Atlantic Ultraviolet Corporation.)*

19.4 OTHER WATER TREATMENTS

(a) Aeration (Oxidation)

This simple process can improve the taste and color of water and help remove iron and manganese. In aeration, as much of the water's surface as possible is exposed to air. The methods used are rich in aesthetic possibilities—the spraying of water into air, the fall of a turbulent stream of water over a spillway, and *flowforms*, sculptural waterfalls designed to carry water in a rhythmical, pulsating, figure-eight pattern. The Real Goods headquarters in Hopland, California, features these as a waterfall (Fig. 19.7) within a recycled water irrigation system.

To guard against contamination, these processes are often enclosed; if exposed, they must be kept clean. For aeration within tanks, water is passed through a series of perforated plates in streams or droplets.

Aeration improves the flat taste of distilled water and cistern water by adding oxygen. It also oxidizes iron or manganese, which then can more easily be removed by filtration. It also removes odors caused by hydrogen sulfide and algae.

Because aeration raises the level of dissolved oxygen in water, it should be avoided as a treatment when corrosion is a threat.

(b) Corrosion Control

It is important to control corrosion both to keep water systems operating freely and to prevent corrosive water from increasing the concentration of hazardous materials (as from copper pipes). Corrosion also imparts a taste and/or odor to water that is objectionable. Corrosion is a slow degradation of a metal by a flow of electric current from the metal to its surroundings. Some factors involved in corrosion control are:

1. *Acidity.* The more acid (low pH, less than 6.0), the more corrosive the water.

(*a*) (*b*)

Fig. 19.7 *The Real Goods Solar Living Center at Hopland, California, uses creative water recycling. Water from on-site irrigation ponds (a) is pumped by PV to a tank on a small hill, and (b) water is also dispersed into the air from the Agave Fountain for evaporative cooling. (Landscape design by Land and Place.) (©Alison Kwok, all rights reserved.)*

2. *Conductivity.* As dissolved mineral salts increase the water's conductivity, they encourage the flow of the electrical current of corrosion.
3. *Oxygen content.* Dissolved oxygen destroys the thin protective hydrogen film on immersed metals, thus promoting corrosion.
4. *Carbon dioxide content.* Carbon dioxide forms carbonic acid, which attacks metal surfaces.
5. *Water temperature.* Increased temperature increases corrosion.
6. *Lower flow rates.* Reduced turbulence means reduced erosion of the protective layers that form on the inner surfaces of pipes.

The products of corrosion often contribute to scale formation. Scale then lines surfaces, eventually clogging openings.

See the National Drinking Water Clearinghouse *Tech Brief* (February 1997), *Corrosion Control*, for details on this subject.

Acid neutralizers can be installed on water supplies with low pH; their function is often combined with those of hypochlorinators. Typically, neutralizing solutions are mixtures of lime, soda ash, and water. However, pH adjustment should be made just before water delivery, *after* treatment processes such as coagulation and disinfection.

Corrosion inhibitors cause protective coatings to form on pipes. They are commonly fed into the water, as are other chemicals. Inorganic phosphates, sodium silicates, and mixtures of phosphates and silicates are the more commonly used additives.

Other corrosion control strategies include commercial pipe coatings/linings, installing dielectric or insulating unions (to avoid complications from dissimilar pipe metals), and avoiding metal piping and fixtures altogether.

(c) Softening

Water hardness is caused primarily by calcium and magnesium deposits; when they are removed, water will be soft. Where water hardness is mild enough to affect only laundering, cisterns may be used to collect soft rainwater to use for washing clothes. Where water hardness produces scale in pipes and water-heating appliances, and cisterns are not feasible, water-softening equipment is used. Demineralization of water is accomplished with one of three methods: ion exchange, reverse osmosis, or electrodialysis.

See the National Drinking Water Clearinghouse *Tech Brief* (May 1997), *Ion Exchange and Demineralization*, for details on the following methods of treatment.

Ion exchange is popular for small systems, and is effective not only with hardness ions but also with radionuclides. It can be used with fluctuating flow rates but requires pretreatment of most surface waters, and its waste is highly concentrated (requiring careful disposal). A large variety of resins are used for the exchange medium, each effective for specific contaminants.

On the exchange medium's charged surface, one (contaminant) ion is exchanged for another (regenerant) ion. Eventually, saturation occurs; the contaminants are flushed and the medium is regenerated—once per day is the common shortest cycle. Sodium chloride is often used to regenerate the exchange medium, resulting in a rather high sodium residual—an undesirable development for people on low-sodium diets. Another regenerant material is potassium chloride.

Equipment includes prefiltration, ion exchange, disinfection, storage, and distribution elements; in smaller systems, single-package units incorporate all of these processes.

Reverse osmosis (RO), like ion exchange, is popular for small systems and can be used with fluctuating flow rates, but it requires pretreatment of most surface waters, and its waste is also highly concentrated. RO is effective not only with hardness ions but also with radium, natural organic substances, pesticides, and microbiological contaminants. RO units used in series can remove an even higher percentage of contaminants.

An inert, semipermeable membrane has a high-pressure supply water on one side; as the pressure slowly forces water through this filtering membrane, most of the contaminants are removed. Water must be used to flush the membrane so that mineral buildup is avoided; this produces a brine requiring careful disposal. Membranes are available in varying types and pore sizes; they are prone to fouling.

Commercial RO units are available in sizes ranging from a 1 gpm (3.9 L/m) water delivery rate (using two membranes and a 3-hp [2.2-kW] motor, requiring 4.5 gpm [17 L/m] feedwater for a 22% recovery rate) to a water delivery rate of 12.5 gpm (47.3 L/m) (using 12 membranes and a 15-hp

[11.2-kW] motor, requiring 19.2 gpm [72.8 L/m] for a 65% recovery rate).

Electrodialysis effectively removes fluoride and nitrate, and can also remove barium, cadmium, and selenium. It is relatively insensitive to levels of flow and of total dissolved solids but has an enormous appetite for water. From 10% to 80% of the total water supplied to an RO filtering unit is delivered to the user; the remainder is a waste stream. It also requires a higher level of pretreatment.

In this process, membranes adjacent to the inflowing stream are charged (either positively or negatively), attracting counter-ions to these membranes. The membranes allow either positively or negatively charged ions to pass through; thus, the ions leave the inflow stream and enter the waste streams (on the other side of each membrane). High water pressure and a source of DC power are needed in this process.

Membranes can become fouled when the pores are clogged by salt precipitation or blocked by suspended particulates. For either of these water conditions, pretreatment is essential. Reversing the charge on the membranes, *electrodialysis reversal*, helps to flush the attached ions from the membrane surface and can extend the time between membrane cleanings.

(d) Nuisance Control

Some organisms may not be injurious to health but can multiply so rapidly that piping or filters become clogged, or the water's appearance, odor, and taste are affected. This situation is most common with surface water sources, and it is within surface reservoirs that these treatments are most often applied. Algae growths, the most prevalent nuisance, can usually be controlled by applying copper sulfate (blue stone or blue vitriol) to the water body. Sudden and massive algae kills can have adverse impacts on other life forms within the water, because the decomposing algae rob the water of oxygen. As a further precaution, stored water should be shielded from sunlight whenever possible.

Cooling towers present an especially difficult water treatment problem. The murky water with high turbidity and a high bacterial count leads to clogged passages (thus inefficient performance), deteriorated surfaces, and the growth of potentially lethal bacteria (*L. pneumophila*). As a result, enormous quantities of water are commonly passed once through a cooling tower, and then dumped into storm sewers rather than being recycled in a closed system. (As late as 1989, San Francisco's City Hall was reported to be using 96,000 gallons [363,000 L] per summer day for once-through cooling—in a year of drought.) To treat cooling tower water successfully, a method is needed for microbial control, removing organics, and precipitating inorganics; ozonation (Fig. 19.5) is a common answer to this widespread treatment problem.

(e) Fluoridation

A heated controversy continues over the addition of fluoride to drinking water. The advantage of fluoridation is that children who drink fluoridated water during the most active stages of tooth development have lower rates of tooth decay. Because everyone drinks water, all children (and adults) benefit, not just those who can afford fluoride pills or prescription toothpaste. Opponents of fluoridation suggest that because sugar is a leading cause of tooth decay in children, sugar, rather than water, should be fluoridated. Small water systems can be equipped with fluoridation units. However, fluoride levels in the water supply must be carefully monitored. In amounts *above* those used in water treatment, fluoride is toxic and can cause mottled teeth.

(f) Distillation

This is a simple, low-technology approach to purification that produces the equivalent of bottled water for drinking, cooking, and laboratory uses. In one process, it promises the removal of suspended solids, salts, bacteria, and (apparently) halogenated hydrocarbons. When water pollution is extreme, as in the case of sea (salt) water, distillation may be the best treatment. Water is heated to encourage evaporation. As the water turns to vapor, virtually all pollutants are left behind. When this vapor encounters a cooler surface, it condenses, and pure water (although flat in taste) can be collected from this surface.

Any heat source can be used in the distilling of water; solar stills (Fig. 19.8) are gaining in popularity because the energy used is free. Solar distillation of cistern water is an autonomous approach. In semiarid, rather sunny climates, a solar still should

Fig. 19.8 A solar still can be used to provide a small daily quantity of pure water; this installation serves a laboratory. (Courtesy of McCracken Solar Co., Alturas, CA.)

produce about ½ gal per square foot (4 L/m^2) of collector surface area per day. This rate of production suggests that only the water used directly for drinking or other specialized purposes is usually feasible for distillation. Another factor to consider is that the cleaning of the still is generally accomplished by flushing it with twice as much water as was delivered. If not excessively brackish, this flush water could be used for irrigation or other non-potable-quality tasks.

19.5 WATER SOURCES

This section focuses on the equipment used to capture and store groundwater from wells. Other water sources are less often used for smaller systems, either because they require much more extensive treatment (surface water from lakes or rivers) or because they provide water intermittently (cisterns). A multistage treatment (flocculation, sedimentation, etc.) may be inappropriate for small water systems that receive only occasional maintenance. Cisterns were discussed in Chapter 18. Another increasingly important source of city water, the treated effluent of sewage treatment plants, is discussed in Chapter 20.

(a) Wells

Farms and remote housing developments usually have private water systems. In rural and suburban areas where the progress of building is faster than the development of municipal water supplies, private sources may also be sought. Driven or drilled wells are preferable; water from these sources usually has at least the advantages of purity, coolness, and freedom from turbidity, odor, and unpleasant taste—any of which may be encountered in well water, in addition to either acidity or hardness.

Bored wells, which are dug with earth augers, are usually less than 100 ft (30 m) deep. They are used when the earth to be bored through is boulder-free and will not cave in. The diameter range is 2 to 30 in. (50 to 760 mm). The bored well is then cased with metal, vitrified tile, or concrete.

Driven wells are the simplest and usually the least expensive type. A steel drive-well point is fitted on the end of pipe sections and driven into the earth. The drive point is usually 1¼ to 2 in. (32 to 50 mm) in diameter. The materials and design of drive-well points vary according to the expected characteristics of the earth in which the well is driven. First, a pilot hole is bored (frequently with a simple hand auger), and the drive-well point and pipe sections are lowered into it. Then the well is driven to a point well below the water table.

Jetted wells require a source of water and a pressure pump. A washing well point is supplied with water under pressure; this loosens the earth and allows the point and pipe to penetrate.

Drilled wells require more elaborate equipment of several types, depending upon the geology of the site. The percussion (or cable-tool) method involves the raising and dropping of a heavy drill bit and stem. Having thus been pulverized, the earth being drilled is mixed with water to form a slurry, which is periodically removed. As drilling proceeds, a casing is also lowered (except when drilling through rock).

Rotary drilling methods (either hydraulic or pneumatic) utilize a cutting bit at the lower end of a drill pipe; a drilling fluid (or pressurized air) is constantly pumped to the cutting bit to aid in the removal of particles of earth, which are then brought to the surface. After the drill pipe is withdrawn, a casing is lowered into position.

Another method is the down-the-hole pneumatic (air) hammer method, which combines the percussion effect with a rotary drill bit.

Local well drillers, who usually use the method most suited to the prevailing geology of a region, can offer useful advice about well construction methods. When clients plan to build in a remote location, the architect and engineer should advise them about water problems. Quality-corrective measures can always be taken and pumping equipment purchased, but the amount of water that can be obtained from the ground, as well as the depth and cost of wells, are important considerations. There are some problem areas where wells several hundred feet in depth will yield as little as 5 gpm (0.3 L/s) or nothing. The cost of drilling a number of exploratory wells may be excessive. Unfortunately, when such difficulties occur, there is often no easy solution. Conferences with neighboring owners, state and federal geologists, and local well drillers can all be helpful.

A low-yield well can be combined with storage tanks so that a pump can run all night, slowly filling tanks to meet the next day's demands.

(b) Pumps

The Hydraulic Institute, a nonprofit trade association of pump manufacturers, has several recommendations for reducing the amount of electricity consumed by pumps. Some of these apply to small water supply systems.

1. Design systems with lower capacity and total head requirements. (Using larger pipe sizes and minimizing the elevation of tanks are examples.)
2. Avoid excessive capacity. It is typically less expensive to add pumping capacity later on if needs increase. Operating a smaller pump closer to its capacity saves energy compared to a larger pump operating well under its capacity.
3. Select the most efficient pump type and size, even if its first cost is greater; life-cycle costs are likely to be lower.
4. Use two (or more) smaller pumps instead of one large one so that excess pump capacity can be turned off.
5. Maintain pumps and system components to avoid efficiency loss.

Three common types of pumps used in well water supply are the positive displacement pump, the centrifugal pump, and the jet pump.

Positive Displacement Pumps. There are two principal types of positive displacement pumps. In a *reciprocating pump*, a plunger moves back and forth within a cylinder equipped with check valves. The cylinder is best located near or below the groundwater level. Water enters the cylinder through an initial check valve (which allows flow in only one direction). As the plunger moves toward this check valve, the water is forced through the second check valve, located within the plunger itself. Then, as the piston returns to its original position, the water is forced upward toward the surface.

A *rotary pump* has a helical or spiral rotor—a turning vertical shaft within a rubber sleeve. As the rotor turns, it traps water between it and the sleeve, thus forcing the water to the upper end of the rotor.

Centrifugal Pumps. This type of pump contains an impeller mounted on a rotating shaft. The rotating impeller increases the water's velocity while forcing the water into a casing, thus converting the water's velocity into higher pressure. Each impeller and casing is called a *stage*; many stages can be combined in a multistage pump. The number of stages depends upon the pressure needed to operate the water supply system, as well as the height to which the water must be raised. The most common centrifugal pumps are those used in deep wells.

The *turbine pump* has a vertical turbine located below groundwater level and a driving motor located higher up, usually over the well casing at grade. A long shaft is thus required between the motor and the turbine. Substantial head clearances for this shaft's removal may be required. Figure 19.9 shows a turbine pump installation for a small community in Long Island, New York. The water is taken from the ground by multistage turbine pumps at depths of several hundred feet (100 ft = 30.48 m). It is delivered to submerged hydropneumatic tanks at a pressure of about 80 psi (about 550 kPa). As water is required in the houses, the air under pressure in the upper part of the tanks forces water through the mains.

Submersible pumps are designed so that the motor can be submerged along with the turbine (Fig. 19.10). The lengthy pump shaft is thus eliminated.

Jet (or Ejector) Pumps. In a jet pump, a venturi tube is added to the centrifugal pump. A portion of the water that is discharged from a centrifugal pump at the wellhead is forced down

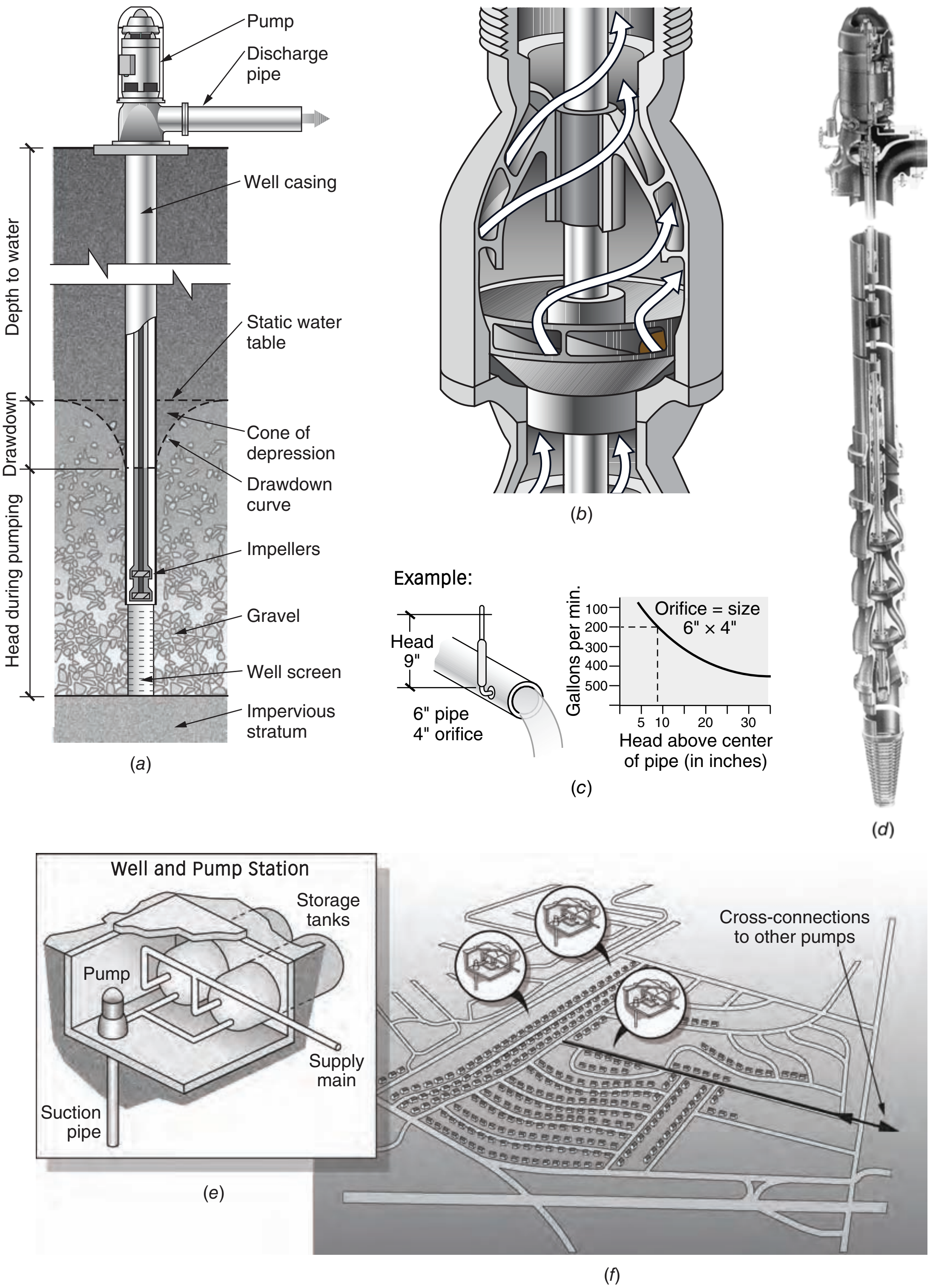


Fig. 19.9 *(a) A turbine well pump. (b) Its operation. (c) Measurement of its capacity. (d) A Jacuzzi multistage lineshaft turbine well pump. (Courtesy of Jacuzzi Bros., Inc.) (e, f) Its use in supplying a small community with groundwater. Capacities of turbine pumps range from 50 gpm to 16,000 gpm (3 L/s to 1010 L/s). (By permission of Progressive Architecture.)*

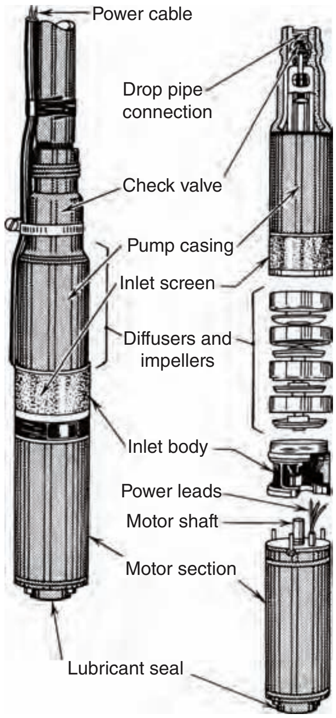


Fig. 19.10 *Submersible pump (centrifugal type) in exploded view. (From the U.S. EPA's* Manual of Individual Water Supply Systems, *1975.)*

to a nozzle and the venturi tube (Fig. 19.11). The lower pressure within the venturi tube induces well water to flow in, and the velocity of the water from the nozzle pushes it up toward the centrifugal pump, which can then lift it more easily by suction.

Pump Selection. Pump variations and characteristics are summarized in Table 19.4. The type of pump selected depends upon many factors, including the rate of yield of a well, the daily flow (and maximum instantaneous flow rate) needed by the users, the size of the storage or pressure tank used, and the total operating pressure against which the pump works (including the height to which water must be raised within the well). First cost, maintenance, and reliability are also factors, as is the energy used by the pump. In cold climates, a pump and water supply system must be protected from freezing.

Of these factors, the two critical selection determinants are the flow rate (volume per minute or per hour to be delivered) and the total pressure (or *head*). The flow rate depends upon the number of fixtures to be served (Fig. 19.12). The total pressure (Fig. 19.13) includes the suction lift, static head, and friction loss plus the pressure head. This relationship will be explained in detail in Section 19.11.

(c) Pressure Tanks

Serving also as water storage, these tanks are frequently used both to maintain a constant pressure on a pump-supplied water system and to allow for temporary peaks in water supply rates that exceed the capacity of the pump. (Elevated tanks offer one alternative to pressure tanks, cisterns another—although the latter usually are not located high enough to provide pressure to the supply system.)

Pressure tanks are often housed in outbuildings, along with the pump and any water treatment equipment (Fig. 19.13). The temperature of the outbuilding must be kept above freezing, and its roof or walls should be removable to allow for replacement of parts over time. One type of pressure (storage) tank is shown in Fig. 19.14.

The capacity of pressure tanks usually is small in comparison to the daily *total* water consumption; they provide short-term responses to peak flow demands. As a general rule, the pressure tank should be sized to deliver about 10 times the pump's capacity in gpm (L/m). For a typical residence, allow 10–15 gal (38–57 L) tank capacity per person served.

For larger installations, the size of a pressure-storage tank can be calculated by

$$Q = \frac{Qm}{1 - \frac{P_1}{P_2}}$$

where

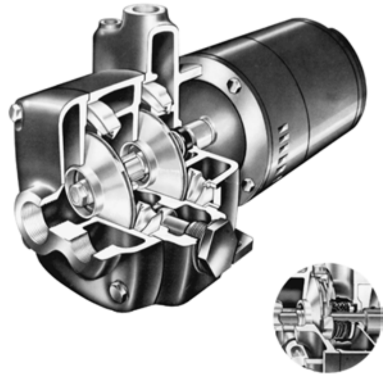
Q = tank volume (gal [L])

Qm = 15 minutes of storage at peak usage rate (gal [L])

P_1 = minimum allowable operating pressure (psi [kPa]) plus atmospheric pressure (14.7 psi [101 kPa])

P_2 = maximum allowable operating pressure (psi [kPa]) plus atmospheric pressure (14.7 psi [101 kPa])

(a)



(c)

(b)

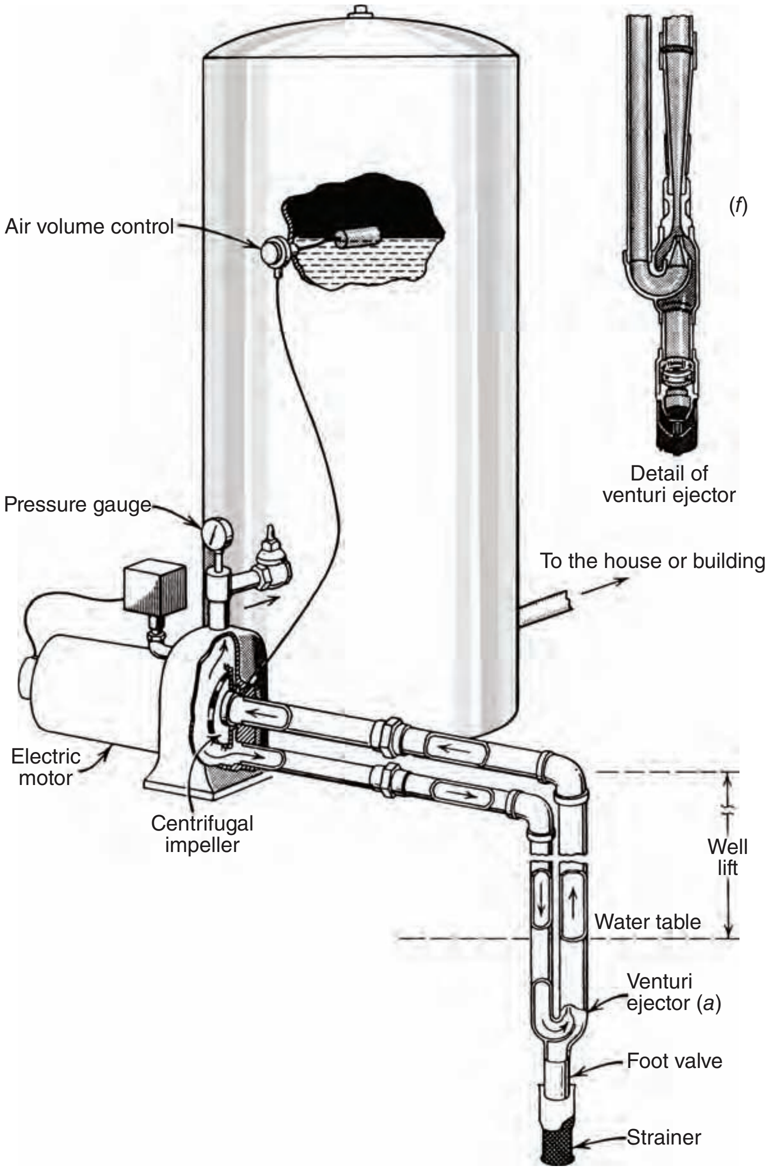
CHOOSE THE CORRECT JH FROM THESE CHARTS
DEEP WELL (Down to 120 feet)

The JH in the 1/2, 3/4, 1 and 1 1/2 horsepower rating. matched with the appropriate injector and pipe sizes. will pump this amount of water at the indicated lift or depth to the water in the well:

If suction lift or depth to water is	1/2 HORSEPOWER	3/4 HORSEPOWER	1 HORSEPOWER	1 1/2 HORSEPOWER
	Produces these gallons per hour between 20-50 lbs. discharge pressure		Produces rhese gallons per hour between 30-60 lbs. discharge pressure	
30 feet	795 G.P.H.	990 G.P.H.	1140 G.P.H.	1620 G.P.H.
40	680	875	1000	1470
50	575	735	875	1300
60	445	630	875	1200
70	360	495	620	920
80	310	385	530	820
90	255	315	435	700
100	220	275	340	590
110	195	240	295	540
120		205	250	480

(d)

Fig. 19.11 *Details of a deep-well jet pump. (a) Photograph of a multistage jet pump housing and equipment. At the top is the on/off electrical switch activated by pressure settings. It controls the direct-connected electric motor to the left. Impellers are enclosed in the pump housing at the right. Circulating connections to and from the jet can be seen to the right; the pump discharge at the top. The pump can be set to operate up to 100 psi (690 kPa). (b) Well casing and circulating lines. Jet element can be seen at the bottom of the left-hand (larger) pipe. (c) Cutaway section of the pump. (d) Pumping capacity in gph under various conditions and discharge pressure ranges of 20 to 50 psi and 30 to 60 psi. (Courtesy of Jacuzzi Bros., Inc.) (e) Jet-type (also known as* venturi *or* ejector*) deep-well pump and storage tank for a house or small building (for well lifts greater than 25 ft [7.6 m]). Reduced pressure at (f), the jet nozzle, induces the flow of groundwater into the circulated flow.*



(e)

Fig. 19.11 *(Continued)*

The ranges of allowable pressures are discussed in Section 19.9. An alternative tank-sizing procedure is shown in Table 19.5.

EXAMPLE 19.1 An office building in a remote location has a water supply system served by a pump and well. The peak demand is 50 gpm (3.15 L/s). The fixtures will operate at a minimum of 50 psi (345 kPa); a maximum of 70 psi (483 kPa) should not be exceeded. Therefore,

$$Qm = 15\,\text{min} \times 50\,\text{gpm} = 750\,\text{gal}$$

$$(15\,\text{min} \times 60\,\text{s}/\text{min} \times 3.15\,\text{L}/\text{s} = 2835\,\text{L})$$

and

TABLE 19.4 Pumps for Water Supply

Type of Pump	Practical Suction Lift[a]	Usual Well-Pumping Depth	Usual Pressure Heads	Advantages	Disadvantages	Remarks
POSITIVE DISPLACEMENT						
1. Reciprocating a. Shallow well b. Deep well	22–25 ft (6.7–7.6 m) 22–25 ft (6.7–7.6 m)	22–25 ft (6.7–7.6 m) Up to 600 ft (183 m)	100–200 ft (30–61 m) Up to 600 (183 m) above cylinder	1. Positive action. 2. Discharge against variable heads. 3. Pumps water containing sand and silt. 4. Especially adapted to low capacity and high lifts.	1. Pulsating discharge. 2. Subject to vibration and noise. 3. Maintenance cost may be high. 4. May cause destructive pressure if operated against closed valve.	1. Best suited for capacities of 5–25 gpm (0.3–1.6 L/s) against moderate to high heads. 2. Adaptable to hand operation. 3. Can be installed in very-small-diameter wells (2-in. [50-mm] casing). 4. Pump must be set directly over well (deep well only).
2. Rotary a. Shallow well (gear type)	22 ft (6.7 m)	22 ft (6.7 m)	50–250 ft (15–76 m)	1. Positive action. 2. Discharge constant under variable heads. 3. Efficient operation.	1. Subject to rapid wear if water contains sand or silt. 2. Wear of gears reduces efficiency.	
b. Deep well (helical rotary type)	Usually submerged	50–500 ft (15–152 m)	100–500 ft (30–152 m)	1. Same as shallow well rotary. 2. Only one moving pump device in well.	1. Same as shallow well rotary except no gear wear.	1. A cutless rubber stator increases life of pump. Flexible drive coupling has been weak point in pump. Best adapted for low capacity and high heads.
CENTRIFUGAL						
1. Shallow well a. Straight centrifugal (single stage)	20 ft max. (6 m)	10–20 ft (3–6 m)	100–150 ft (30–46 m)	1. Smooth, even flow. 2. Pumps water containing sand and silt. 3. Pressure on system is even and free from shock. 4. Low-starting torque. 5. Usually reliable and good service life.	1. Loses prime easily. 2. Efficiency depends on operating under design heads and speed.	1. Very efficient pump for capacities above 60 gpm (3.8 L/s) and heads up to about 150 ft (46 m).
b. Regenerative vane turbine type (single impeller)	28 ft max. (8.5 m)	28 ft (8.5 m)	100–200 ft (30–61 m)	1. Same as straight centrifugal except not suitable for pumping water containing sand or silt. 2. They are self-priming.	1. Same as straight centrifugal except maintains priming easily.	1. Reduction in pressure with increased capacity not as severe as straight centrifugal.

(cont'd)

TABLE 19.4 Pumps for Water Supply (*Continued*)

Type of Pump	Practical Suction Lift[a]	Usual Well-Pumping Depth	Usual Pressure Heads	Advantages	Disadvantages	Remarks
			CENTRIFUGAL (*Continued*)			
2. Deep well a. Vertical line shaft turbine (multistage)	Impellers submerged	50–300 ft (15–91 m)	100–800 ft (30–245 m)	1. Same as shallow well turbine. 2. All electrical components are accessible above ground.	1. Efficiency depends on operating under design head and speed. 2. Requires straight well large enough for turbine bowls and housing. 3. Lubrication and alignment of shaft critical. 4. Abrasion from sand.	
b. Submersible turbine (multistage)	Pump and motor submerged	50–400 ft (15–122 m)	50–400 ft (15–122 m)	1. Same as shallow well turbine. 2. Easy to frost-proof installation. 3. Short pump shaft to motor. 4. Quiet operation. 5. Well straightness not critical.	1. Repair to motor or pump requires pulling from well. 2. Scaling of electrical equipment from water vapor critical. 3. Abrasion from sand.	1. 3500 RPM models, although popular because of smaller diameters or greater capacities, are more vulnerable to wear and failure from sand and other causes.
			JET			
1. Shallow well	15–20 ft (4.6–6.0 m) below ejector	Up to 15–20 ft (4.6–6.0 m) below ejector	80–150 ft (24–46 m)	1. High capacity at low heads. 2. Simple in operation. 3. Does not have to be installed over the well. 4. No moving parts in the well.	1. Capacity reduces as lift increases. 2. Air in suction or return line will stop pumping.	
2. Deep well	15–20 ft (4.6–6.0 m) below ejector	25–120 ft (7.6–37 m) 200 ft max. (61 m max)	80–150 ft (24–46 m) 2. Well straightness not critical.	1. Same as shallow well jet. 2. Lower efficiency, especially at greater lifts.	1. Same as shallow well jet.	1. The amount of water returned to ejector increases with increased lift—50% of total water pumped at 50-ft (15-m) lift and 75% at 100-ft (30-m) lift.

Source: U.S. Environmental Protection Agency, *Manual of Individual Water Supply Systems*, 1975. (SI units added by authors of this book.)

[a]Practical suction lift at sea level. Reduce lift 1 ft (0.3 m) for each 1000 ft (305 m) above sea level.

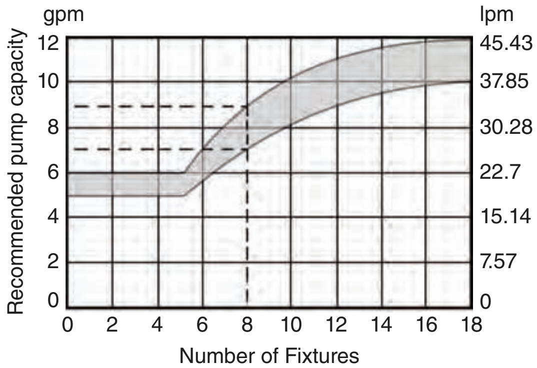


Fig. 19.12 The relationship between the recommended flow-rate capacity of a pump and the number of domestic plumbing fixtures it supplies. (Redrawn with SI units by Nathan Majeski; from the U.S. EPA's Manual of Individual Water Supply Systems, *1976.)*

$$Q = \frac{Qm}{1-\frac{P_1}{P_2}} = \frac{750}{1-\frac{50+14.7}{70+14.7}} = \frac{750}{1-0.76}$$

$$= 3125\ \text{gal}$$

$$\left[= \frac{2835}{\left(1-\left(\frac{345+101}{483+101}\right)\right)} = \text{apx. } 12{,}000\ \text{L} \right]$$

■

The capacity of elevated tanks usually is equal to at least 2 days of average water usage. For fire-fighting or other special requirements, the capacity may have to be even greater.

A summary of the quality, treatment, and supply issues raised thus far is provided in the example of a rural estate shown in Fig. 19.15 and Table 19.5. On this large estate, water was required for an estimated demand of 30,000 gpd (113,560 Lpd). This was for domestic use only; irrigation was served by a separate installation pumping from a lake. Wells were dug for the domestic supply. It was quickly evident that, despite the great depths of the wells

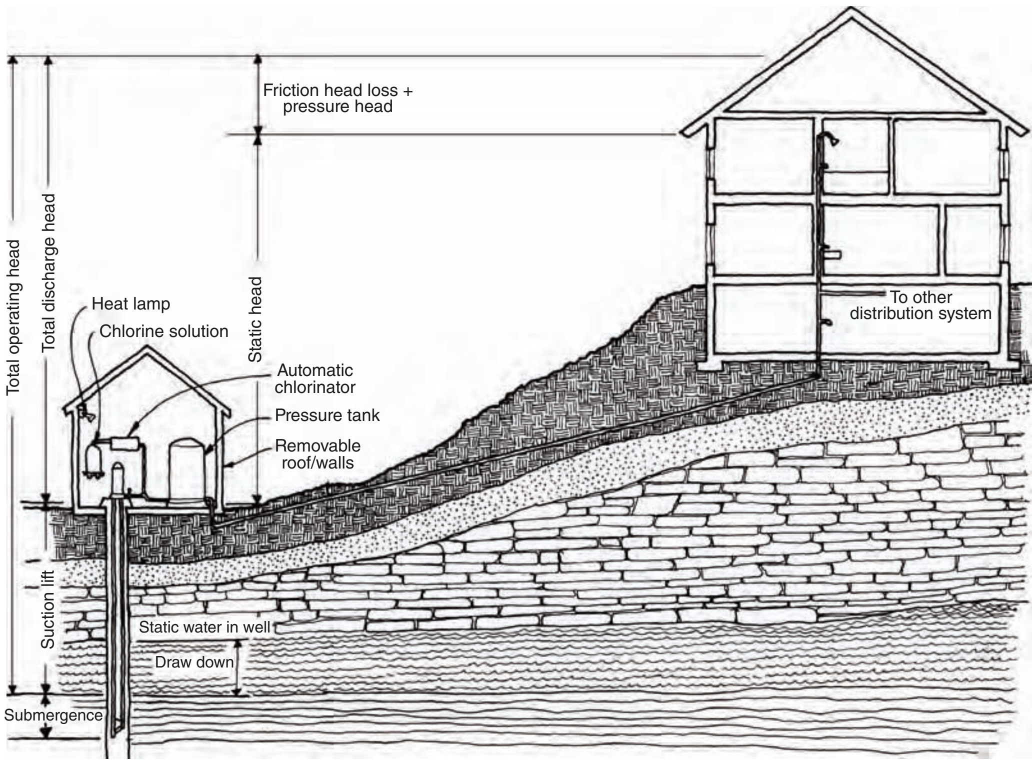


Fig. 19.13 The components of the total operating pressure (or head), a critical determinant of pump size. The pumphouse is usually a separate structure with water treatment and storage components. (From the U.S. EPA's Manual of Individual Water Supply Systems, *1975.)*

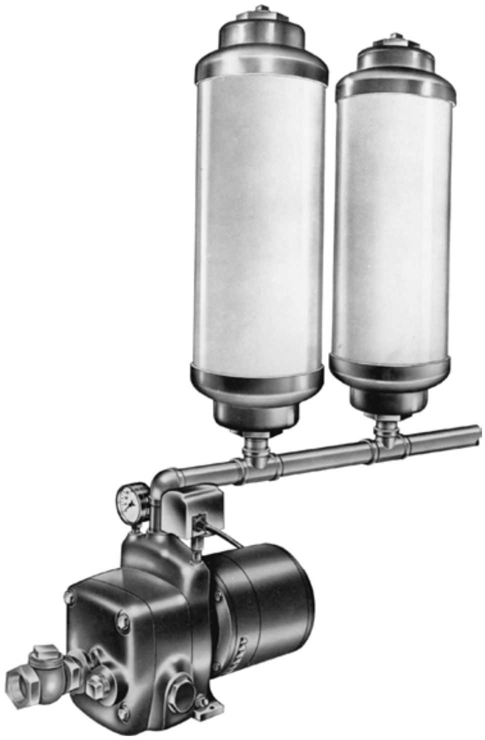


Fig. 19.14 *Small pressure tanks are installed primarily to keep a water supply system at constant pressure. These Hydrocel models are small: 8½ in. (216 mm) in diameter, 27 in. (686 mm) long; they can be installed almost anywhere along the supply system. (Courtesy of Jacuzzi Bros., Inc.)*

drilled, the available flow would be small. Four wells yielded a total rate of only 25 gpm (1.6 L/s).

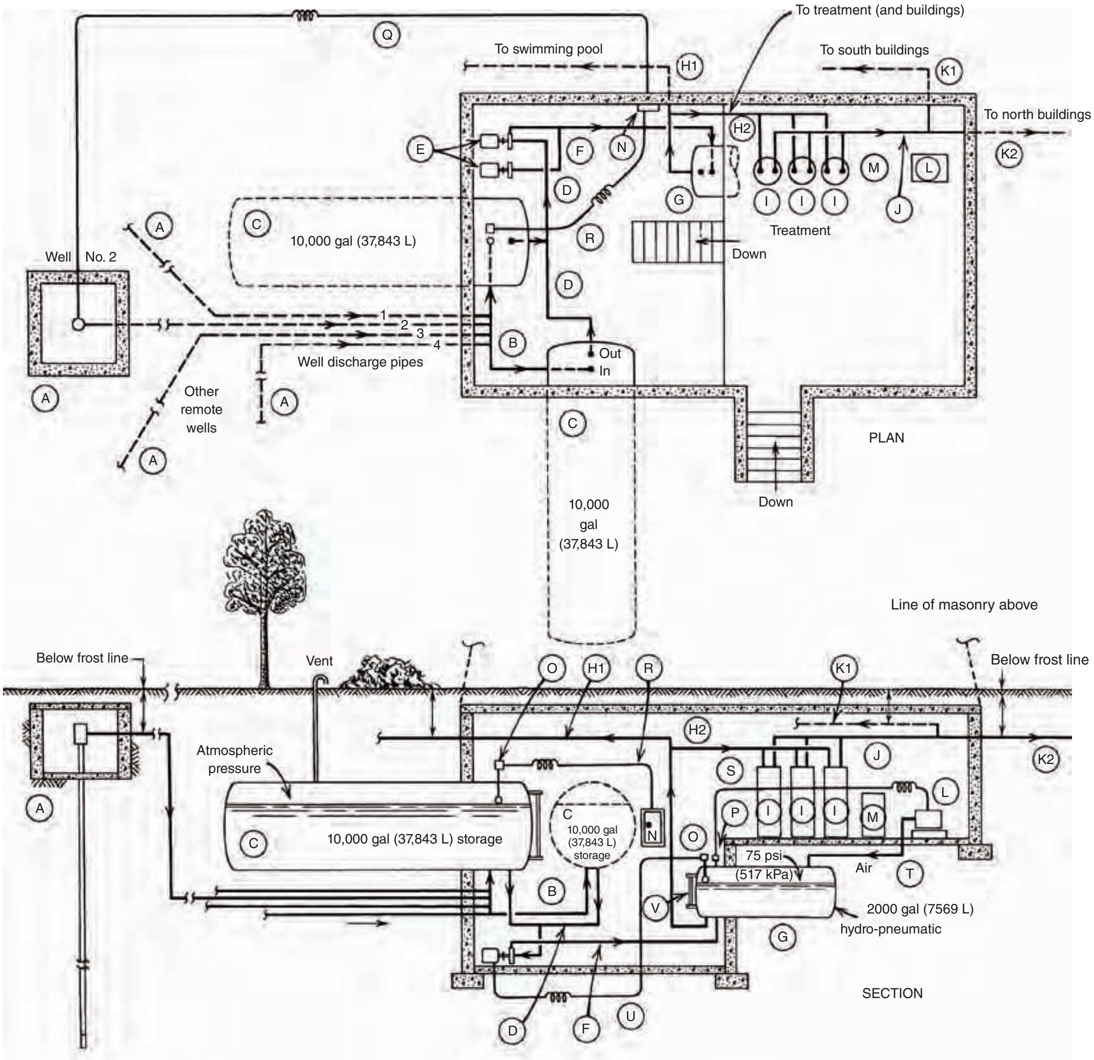
Calculations for the amount of water to be stored to supplement this meager supply are shown in Table 19.5. The table shows that during the 14 daytime hours under conditions of peak demand, the well pumps would run continuously. Concurrently, an additional 9000 gal (34,065 L) would be drawn from the tanks. At night, the well pumps would run for 6 hours to restore the 9000 gal (34,065 L) drawn from the tanks during the day.

The operation of the system is illustrated in the diagram and notes of Fig. 19.15*a.* The pressure of 75 psi (517 kPa) in the hydropneumatic tank is sufficient to raise the water to the greatest height in the distribution system, overcome friction in the piping, and leave a residual pressure available at each fixture of about 10 to 15 psi (69 to 103 kPa). Excessive pressure can always be moderated by a valve in the branch supply of the fixture.

Pressure in this tank is ensured by the air compressor, activated by a pressure switch. A float switch starts the centrifugal pump to deliver water from the storage tanks as needed. The storage tanks, piped together and acting as a single reservoir, are fed by the four wells. The wells operate in unison, singly, or in groups, depending upon the level in the storage tanks. If the level drops rapidly, all well pumps can run. Although they are arranged to operate all day when needed, during periods of minimum demand only one or two may be called upon. Each has its own power supply, but controls emanate from panel *N.*

TABLE 19.5 Calculations to Establish Capacity of Water Storage Tanks at Kinloch (Fig. 19.15)

1. Potable domestic water demand per day	30,000 gpd (113,550 L/d)
2. Assumed hours of use	7:00 A.M. to 9:00 P.M. (14 hours)
3. Assumed hours of virtual nonuse	9:00 P.M. to 7:00 A.M. (10 hours)
4. Well-yield rate per hour	25 gpm × 60 min = 1500 gph (1.6 L/s × 60 × 60 = 5679 L/h)
5. Total well yield in 14 hours	1500 gph × 14 hr = 21,000 gal (5679 L/h × 14 h = 79,506 L)
6. Total water needed in 14 hours	30,000 gal (113,550 L)
7. Well yield in 14 hours	21,000 gal (79,506 L) [see step 5]
8. Net-tank capacity required, minimum	30,000 – 21,000 = 9000 gal (113,550 – 79,506 = 34,044 L)
9. Net-tank capacity as designed with two tanks at 10,000 gal (37,850 L) each:	20,000 × 0.80 (80% full) = 16,000 gal (75,700 × 0.8 [80% full] = 60,560 L)
and one tank at 2000 gal (7570 L)	2000 gal × 0.70 (70% full) = 1400 gal (7570 L × 0.7 [70% full] = 5300 L)
	total capacity = 17,400 gal (65,860 L); which is OK, greater than 9000 gal (34,044 L) as per step 8
10. Well operation at night to restore 9000 gal (34,065 L) to tanks	9000 ÷ 1500 = 6 hours of the 10 night hours available (34,065/5679 = 6 h)



Legend

A	Wells	L	Air compressor maintains 75 psi in tank
B	Well water header for four wells	M	Sodium chloride for regeneration
C	Well water storage, vented tanks, (atmospheric pressure)	N	Electrical control panel
D	Pump supply pipe	O	Float switches
E	Electric centrifugal pumps (one is a standby)	P	Pressure switch (actuates air compressor)
F	Pump-discharge to hydro-pneumatic tank	Q	Control wiring to well pumps
G	Hydro-pneumatic tank, 75 lbs per in.^{2} (517 kPa)	R	Control wiring, float switch to panel
H1 H2	Discharge pipes, pressurized well water	S	Control wiring, pressure switch to compressor
I	Water softeners (ion exchangers)	T	Compressed air piping
J	Treated well water under pressure	U	Control wiring, float switch to centrifugal pump
K1 K2	Branch mains to buildings (treated well water)	V	Gauge glass indicates water level

This schematic diagram shows system components and connections. For clarity, details (valves, drains, checkvalves, etc.) are not shown. All control wiring, here simply indicated, operates through control panel N. See text for operation.

(*a*)

Fig. 19.15 *(a) Schematic diagram of the water control and distribution center for the Kinloch Estate. (Courtesy of Bentel & Bentel, Architects, FAIA.) The plant is located on a hillside below the bathing and dressing pavilion. (b) One of two pavilions adjacent to the swimming pool that serves residents and guests at Kinloch. Below this pavilion is the control center. Exterior tubing to and from the control center is all below grade.*

(b)

Fig. 19.15 (Continued)

Swimming pools should be supplied with pure, potable water. Biological tests showed that this well water was safe. Thus, the fill line to the swimming pool is connected from this system rather than from the lake water supply used for irrigation. Because swimming pool water is separately recirculated and provided with its own purification treatment at a location adjacent to the pool, the supply line for makeup water to the pool would have infrequent and off-hour use. Water for domestic use in the buildings is passed through one of three ion exchangers to provide softening and to make the water more suitable for washing, bathing, and cooking. Periodically, the calcium precipitate can be flushed out and the tanks regenerated by sodium chloride.

19.6 HOT WATER SYSTEMS AND EQUIPMENT

There are many ways to provide the "domestic" or "service" hot water needs within a building—the hot water used *not* for space heating, but for bathing, clothes washing, dishwashing, and other related functions. Whereas much of the world either heats such water on a cookstove or does without it, North Americans enjoy an array of choices for domestic hot water (DHW) supply systems. In this section, rough supply estimates are considered first, then basic design choices, conventional heater tanks, solar water heaters, and finally, energy recovery heaters.

With today's better-insulated buildings, the demand for space heating can fall to a level about equal to DHW. As a result, a trend is developing toward using one rather larger water heater designed to meet the need both for space heating and for DHW. This saves both floor space and equipment cost, compared to the more conventional boiler for space heating and a separate water heater for DHW. Some restrictions apply; the 2006 *International Plumbing Code* restricts the maximum potable hot water temperature to 140°F (60°C) and requires water in such a system to remain potable.

TABLE 19.6 Representative Hot Water Temperatures

	Temperature	
Use	**°F**	**°C**
Lavatory		
Hand washing	105	40
Shaving	115	45
Showers and tubs	110	43
Therapeutic baths	95	35
Commercial and institutional laundry (based on fabric)	Up to 180	Up to 82
Residential dishwashing and laundry	140	60
Surgical scrubbing	110	43
Commercial spray-type dishwashing[a]		
Wash	150 minimum	65 minimum
Final rinse	180 to 195	82 to 90

Source: Reprinted with permission; ©ASHRAE, 2011 *ASHRAE Handbook—HVAC Applications.*

[a]For other types of commercial dishwashers, see the 2011 *ASHRAE Handbook—HVAC Applications*.

(a) Water Temperature

Higher water supply temperatures have several advantages but carry the risk of scalding. Although water becomes uncomfortably hot to the touch above 110°F (43°C), much higher temperatures are often used for some commercial processes, as shown in Table 19.6. When determining the temperature at which DHW is to be supplied, consider the following factors.

High Temperatures

- Allow the installation of smaller storage tanks (less hot water is mixed with cold water to achieve a final usage temperature at the shower, sink, or lavatory) but require larger heating units.
- Can be achieved at the point of use (rather than in the tank) by heaters built into equipment such as dishwashers.

- Can cause scale to form on heating coils and within piping (above 140°F [60°C] in areas of hard water quality).
- May be required by code for some applications but limited by code for others.
- Limit the potential for growth of *Legionella pneumophila* bacteria (above 140°F [60°C]).

Lower Temperatures

- Are less likely to cause burns but may not achieve desired sanitation.
- Mean less energy consumed, because storage and pipe heat losses are lower.
- Allow the installation of smaller heating units but require larger storage tanks.
- Make possible the use of lower-grade heat sources for DHW, such as solar energy or waste heat recovery. Table 2.1 shows that around 13% of annual U.S. energy usage is for DHW, which requires the lowest-grade heat source of all the common usages.

(b) Heat Sources and Methods

These include familiar concentrated-energy, high-grade sources such as natural gas and electricity. Oil- and coal-fired boilers are frequently equipped with DHW coils as well. Buildings served by steam may use steam as a DHW heat source. Cogeneration provides heat for DHW, as in Fig. 12.129. Because of the relatively low-grade final temperatures needed, DHW can also be readily provided by wood-burning equipment, incinerators, solar energy equipment, heat pumps, and heat recovery devices (as in commercial ice-making machines whose discharged heat is contributed to DHW).

Heating Methods. There are two basic methods:

1. *Direct* heating brings water in contact with directly heated surfaces: electric-resistance elements or other electrically warmed surfaces within tanks, or surfaces directly exposed to fire or hot gases.
2. *Indirect* heating can be accomplished in several ways. Coils containing steam or fluids can be submerged within water tanks or (Fig. 19.16) set within boilers, whose primary function usually is to provide space or industrial process heating. Alternatively, coils containing DHW can be placed outside a boiler but within a casing containing steam, hot exhaust gases, or very hot water.

Direct and indirect methods can be utilized in a variety of equipment:

Storage tank water heaters, the type most commonly used for residential and small commercial purposes (see Section 19.6*h*)

Circulating storage water heaters, in which the water is first heated by a coil, then circulated through a storage tank (as in some solar heaters—see Section 19.6*i*)

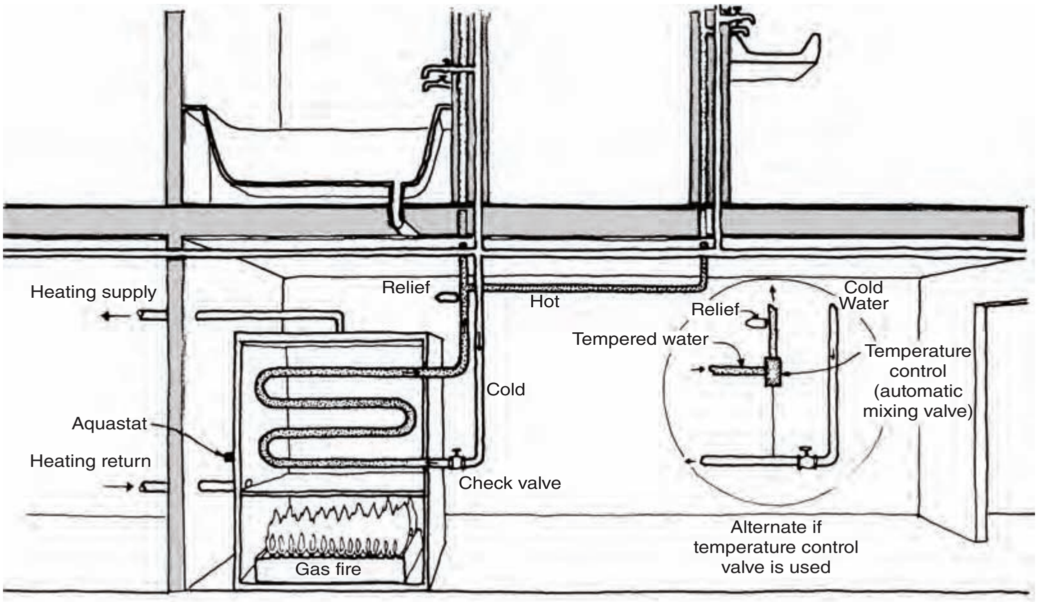
Tankless (*instantaneous*) *heaters*, in which the water is very quickly raised to the desired temperature within a heating coil and immediately sent to the point of usage

(c) Tankless Water Heaters

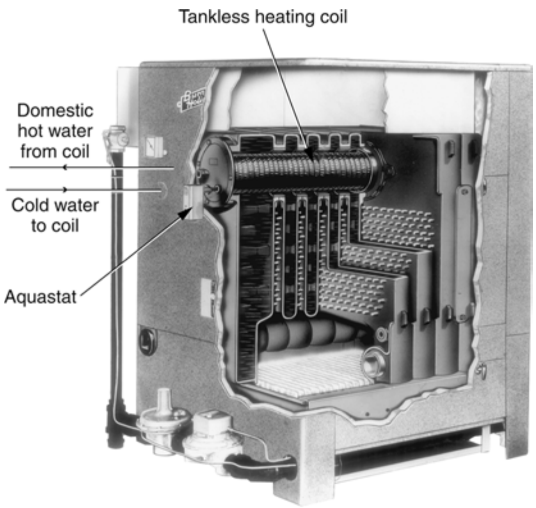
Also called *instantaneous water heaters*, these are available in larger sizes for central hot water systems (Fig. 19.16) or in smaller sizes for wall mounting adjacent to remote plumbing fixtures that occasionally need hot water, or for isolated bathrooms, laundry rooms, and so forth. Decentralized tankless units can be as small as "instant hot water taps" for kitchen or bar sinks—electric-resistance heaters capable of generating perhaps 3 gph at up to 200°F (11 L/h at up to 93°C). Bathroom groups can use either electric resistance or gas-fired units (Fig. 19.17); electric heaters require very high amperage and only about one-third of the primary source energy is delivered as electricity; gas heaters must be vented and are most efficient without continuously burning pilots.

These tankless heaters can be very small; one unit of only 2.65 ft^3 (0.08 m^3) produces up to 4 gpm (0.25 L/s) with a temperature rise of 45F° (20C°). With a greater temperature rise of 100F° (55.5C°), the flow rate drops to somewhat less than half. Because tankless heaters often consist of fairly long coils through which the water passes as it is heated, they may add considerable friction to the total supply system design requirements (see Section 19.11).

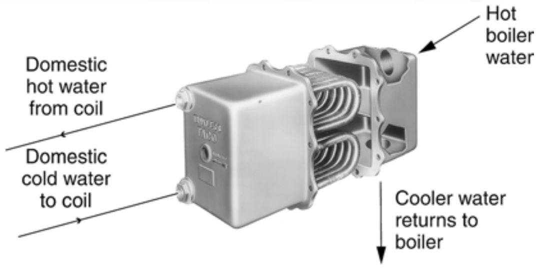
To gain a better understanding of hot water used per activity, and the role of instantaneous heaters, see Table 19.7. Domestic water system design usually concentrates on the storage tank size (see Section 19.6*h*).



(*a*)



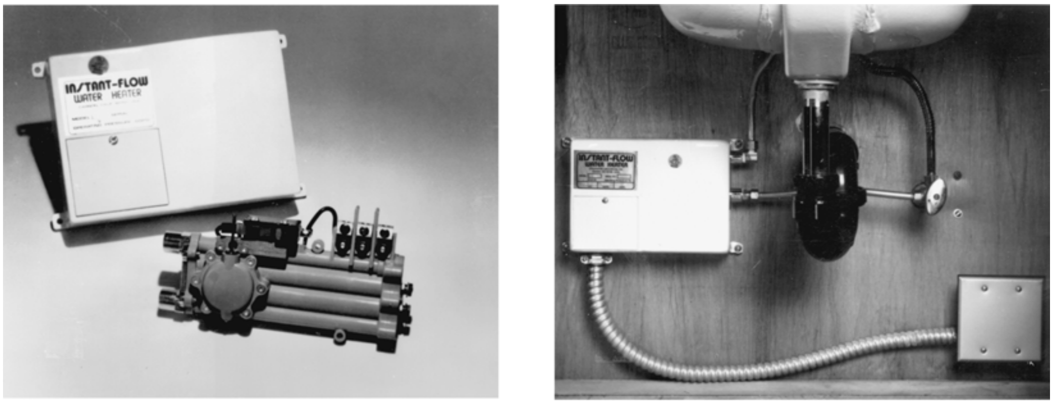
(*b*)



(*c*)

(*d*)

Fig. 19.16 *(a) Example of an indirect, tankless heater for DHW utilizing a boiler that provides hot water for space heating. Because no storage is used, the point of DHW use should be very close to the boiler. (b) Internal tankless heating coil for DHW immersed in the jacket water of a gas-fired hot water heating boiler. The approximate capacity range is 3 to 15 gpm at a 100F° rise (0.2 to 0.9 L/s at a 55C° rise). (c) External-type tankless heater for DHW. Boiler water is piped to the unit and circulates by gravity, transferring heat to the coil. The approximate capacity range is 3 to 15 gpm at a 100F° rise (0.2 to 0.9 L/s at a 55C° rise). (d) A compact, gas-powered, tankless water heater for DHW.* Note: *Because it can be highly inefficient to provide summertime DHW with a boiler designed for winter space-heating loads, codes may alter or prohibit this arrangement.*



(*a*) (*b*)

Fig. 19.17 *Instantaneous or tankless water heater. (a) In this* instant-flow *water heater, a series of coils heats water as it flows through. (b) Installation below a lavatory. A wide range of sizes is available; the 4.6-kW unit raises water temperature by 31F° (17.2C°) at 1 gpm (0.06 L/s); the 9-kW unit raises temperature by 61F° (33.9C°) at 1 gpm (0.06 L/s). (Courtesy of Chronomite Laboratories, Inc.)*

(d) Energy Factors

The U.S. Department of Energy developed the *energy factor* as a standardized measure of annual overall efficiency. Standard storage tank water heaters that are gas-fired may reach an energy factor (EF) of 0.60 to 0.64. Because they have virtually none of the stand-by losses of storage tank heaters, gas-fired tankless water heaters offer EFs of up to 0.69 with continuous pilots and as high as 0.93 with electronic ignition (although this minor usage of electricity is not included in the EF rating).

Some gas-fired instantaneous heaters are designed to operate with battery-powered pilot light ignition. These are useful in remote installations with propane but without electricity.

(e) Central versus Distributed Equipment

This choice can be particularly complex. In the United States, a central water-heater storage tank is standard equipment in homes and small stores. However, the growing use of solar water heating, along with awareness of the heat losses from water-heater storage tanks, has created new interest in *combinations* of central and distributed DHW.

Consider a large residential DHW application such as that shown in Fig. 19.18. Here, two areas where hot water is used are separated by some 50 ft (15 m). If the simple, centralized water-heater storage tank is used (Fig. 19.18*a*), it would probably be placed nearest the maximum-use fixtures—dishwashers and clothes washers. (Also, floor

TABLE 19.7 Domestic Hot Water Consumption—Residences

	Hot Water Required in Gallons (Liters) per Use	
Clothes Washing Machine	*14-lb (6.4-kg) Machine*	*18-lb (8.2-kg) Machine*
Hot wash/hot rinse	38 gal (144 L)	48 gal (182 L)
Hot wash/warm rinse	28 gal (106 L)	36 gal (136 L)
Hot wash/cold rinse	19 gal (72 L)	24 gal (91 L)
Warm wash/cold rinse	10 gal (38 L)	12 gal (45 L)
Dishwashing	*Small*	*Large*
Dishwashing machine	10 gal (38 L)	15 gal (57 L)
Sink washing	4–8 gal (15–30 L)	
Personal Hygiene		
Tub bathing	12–30 gal (45–134 L)	
Wet shaving/hair washing	2–4 gal (8–15 L)	
Showering	2–6 gpm (13–38 L/s)	

Source: Reprinted by permission from Russell Plante, *Solar Domestic Hot Water,* copyright © 1983 by John Wiley & Sons.

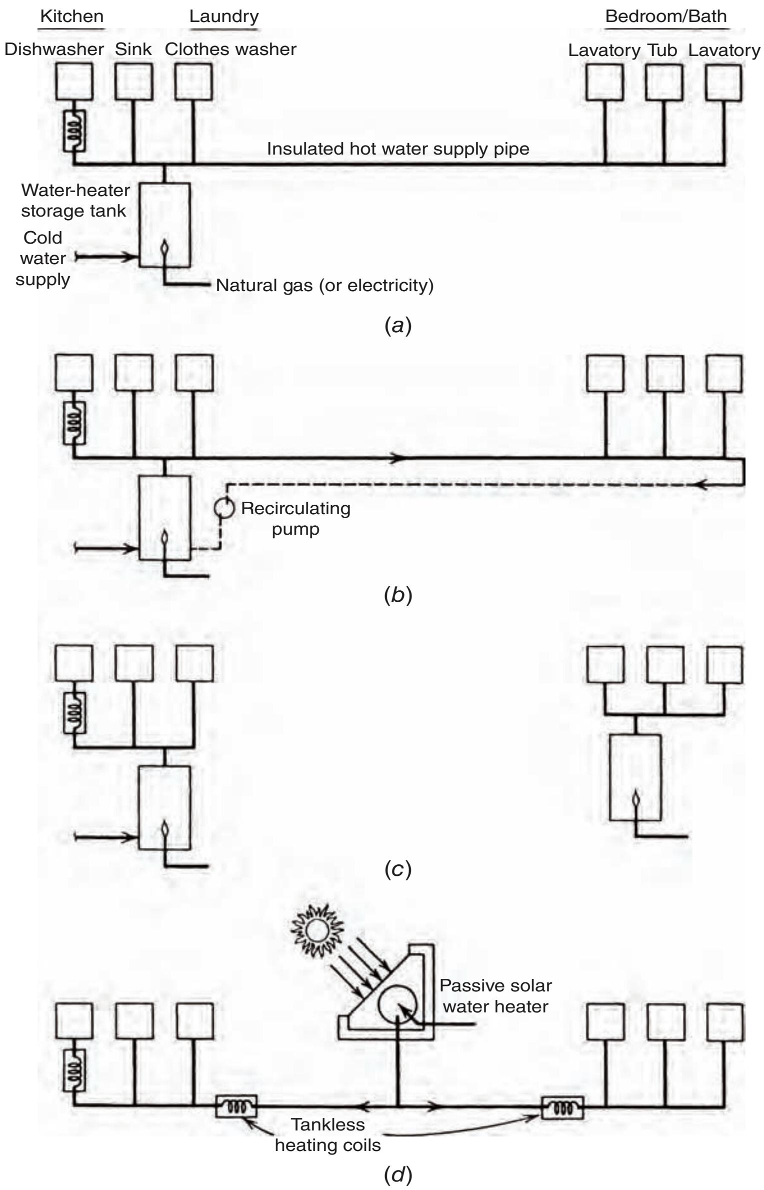


***Fig. 19.18** Options for DHW in a larger residence. (a) Typical centralized water-heater storage tank; water and energy are wasted in the approximately 50-ft (15-m) run involved. (b) Recirculating pump added; this saves water but requires continuous energy to operate the pump and make up the pipe's heat losses. (c) Decentralized approach using two water-heater storage tanks; this roughly doubles the energy lost from storage but eliminates water and energy loss from the long pipe run. (d) Central solar water heater/decentralized tankless heating coil combination; it saves on water and energy but not on initial cost.*

space for the water-heater storage tank is usually more plentiful there.) Codes typically require that at least the first 8 ft (2.4 m) of the hot water pipe be insulated, as it leaves the water heater. However, each time hot water is needed in the remote bathroom serving the bedrooms, the previously heated water in at least 50 ft (15 m) of supply pipe will almost certainly have cooled—despite insulation even over its entire length—and must be drained off before hot water finally arrives. A ¾-in. diameter pipe, for example, will hold 4.6 gal (17.4 L) in 50 ft (15 m) of pipe; if the water heater is set at an energy-conserving temperature of 120°F (49°C) and the incoming city water is 50°F (10°C), the 4.6 gal (17.4 L) of wasted water will also waste the 2682 Btu (2830 kJ) invested during its heating.

Another way to conserve water is with a recirculating hot water system (Fig. 19.18*b*). The primary disadvantages of this system are the increased heat loss through the hot water pipe (now kept at 120°F [49°C] for 24 hours per day rather than for just a few minutes) and the energy required to run the circulating pump (again for 24 hours daily). Codes typically require a conveniently located cut-off switch for the circulating pump and pipe insulation with a minimum k = 0.3 Btu in./h ft^2 °F (0.04 W/m K) over the entire length of the circulating hot water system.

A decentralizing option (Fig. 19.18*c*) is to install two water-heater storage tanks, one for each group. The first cost will be greater and more floor space required. The daily waste heat from *two* heaters is clearly a disadvantage that will at least partially offset the energy saved by eliminating the 50-ft (15-m) run of pipe. (Furthermore, in warm weather this waste heat will add to discomfort within the house.)

A decentralized-centralized mix (Fig. 19.18*d*) will save energy, water, and floor space, but it will almost certainly be costlier to install. A central solar water heater—either passive (shown) or active—brings the water up to warm (winter) or very hot (summer) temperatures. At each fixture group, a tankless heating coil instantaneously heats the water as needed. Almost no water is wasted, and the energy lost in the 50 ft (15 m) of pipe will be solar energy, not purchased energy from natural gas or electricity.

Another option is to omit the solar water heater and simply install two tankless heaters. The primary disadvantage of this setup is the need for larger-capacity heaters, whose instantaneous demand for energy could lead to electric cost penalties in areas where peak-load rates are high. Compared to central storage tanks, however, less heat is lost.

(f) Distribution Trees

The choice of a distribution tree for a central water heating system must take into account the gradual cooling of water within the distribution system once it has left the central heater. If the heat losses associated with constantly circulating hot water (looped trees) are preferable to the heat and water wastage associated with simple, single hot water distribution trees, such loop systems can be achieved in either of two ways.

Thermosiphon hot water circulation depends upon the fact that water expands and becomes lighter when heated, as can be seen in Fig. 19.19*a*. If heat is applied to the lower loop of a glass tube, both ends of which have been inserted in an inverted bottle containing water, the water moves from *A* to *B* and rises through tube *BC* into the bottle. There it becomes cooled and drops through tube *DA* to *A*, is again heated, and rises in tube *BC*—thus completing the circulation. Because the movement depends upon the difference in weight between the two columns of water, the velocity and consequent effectiveness of the circulating system increase as both the temperature of the water and the height of the circuit increase. Hot water supply systems therefore usually consist of a heater with a storage tank, piping to carry the heated water to the farthest fixture, and a continuation of this piping to return the unused cooled water back to the heater. A constant circulation is thereby maintained, and

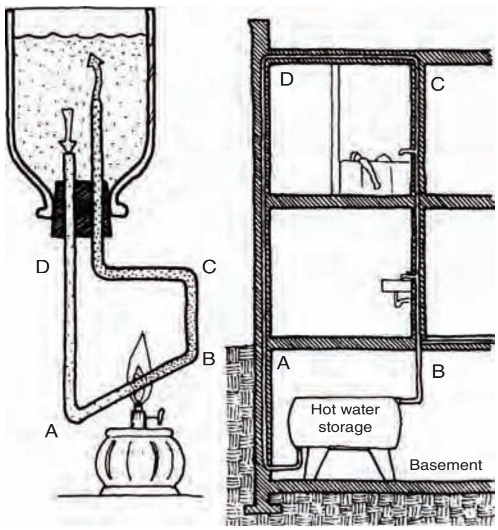


Fig. 19.19 *(a) Principle of hot water circulation by gravity (thermosiphon). (b) Its application to hot water service. During periods of no demand, there is sufficient incidental cooling between* C *and* D *so that dense (less warm) water at* A *forces the lighter (hot) water at* B *to rise for speedy availability at each faucet.*

hot water may be drawn at once from a fixture without first draining off through the faucet the cooled water that would be standing in the supply pipe if there were no recirculation. Because heat increases the corrosive action of water on metals, copper tubing or rated polyvinyl chloride (PVC) pipe is often chosen for use in hot water and hot water circulating systems. Thermosiphon circulating systems are particularly effective in multistory buildings because of the beneficial effect of the increased circuit height on circulation.

Forced circulation of hot water is often utilized where a height advantage is unavailable. Low, long, rambling buildings, such as some large one-story residences, schools, and factories, lack the height needed to set up good hot water circulation by gravity. Also, flow is diminished by friction in long pipe runs. For such buildings, the forced-circulation scheme shown in Fig. 19.20 offers one option. Three independent aquastats—devices that create an electrical signal when water temperature drops—control this system. Aquastats *A*, *B*, and *C*, respectively, sense the temperatures of the water in the heater, in the tank, and at the end of the circulation-return main. As needed, they turn on the oil or gas burner, the tank-circulating pump, and the system-circulating pump. Fixtures remote from the tank are as close to hot water as the length of their hot water runout pipes. Water is usually available at full temperature in 5 to 10 seconds. Trial aquastat settings in °F could be *A* 180, *B* 160, *C* 120 (°C: *A* 82, *B* 71, *C* 49).

(g) Variable Storage Temperature

Energy-saving computer controls are available for hotels, motels, apartments, and larger commercial buildings. These devices (Fig. 19.21) vary the supply temperatures of hot water so that the hottest water is supplied at the busiest hours. In hours of low usage, much lower supply temperatures mean that more hot water will be mixed with less cold water at showers, lavatories, and sinks. This increased hot water quantity poses no problem at off-peak hours, and the lower temperature means significant decreases in heat loss from the recirculating supply water system. A typical payback period is 1 year. Many of the devices store the typical daily patterns of usage in their memory banks, and vary the supply temperature accordingly.

(h) Conventional Water Heater Selection

One of the most common appliances used in the United States is the water-heater storage tank, an

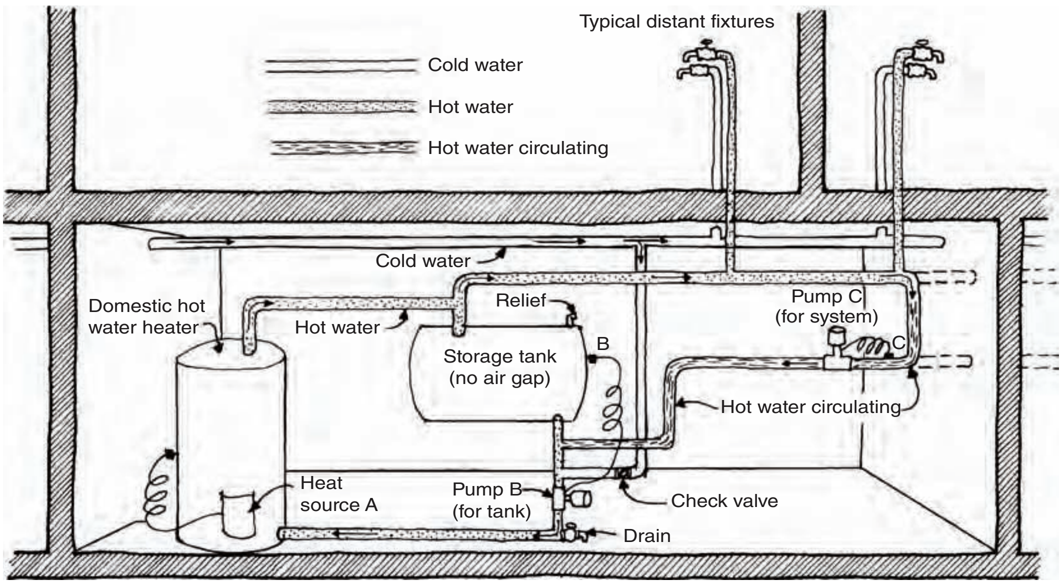


Fig. 19.20 Forced circulation of DHW for a long, low building. (Note that the use of space-heating boilers for DHW may cause system inefficiencies in warm weather.)

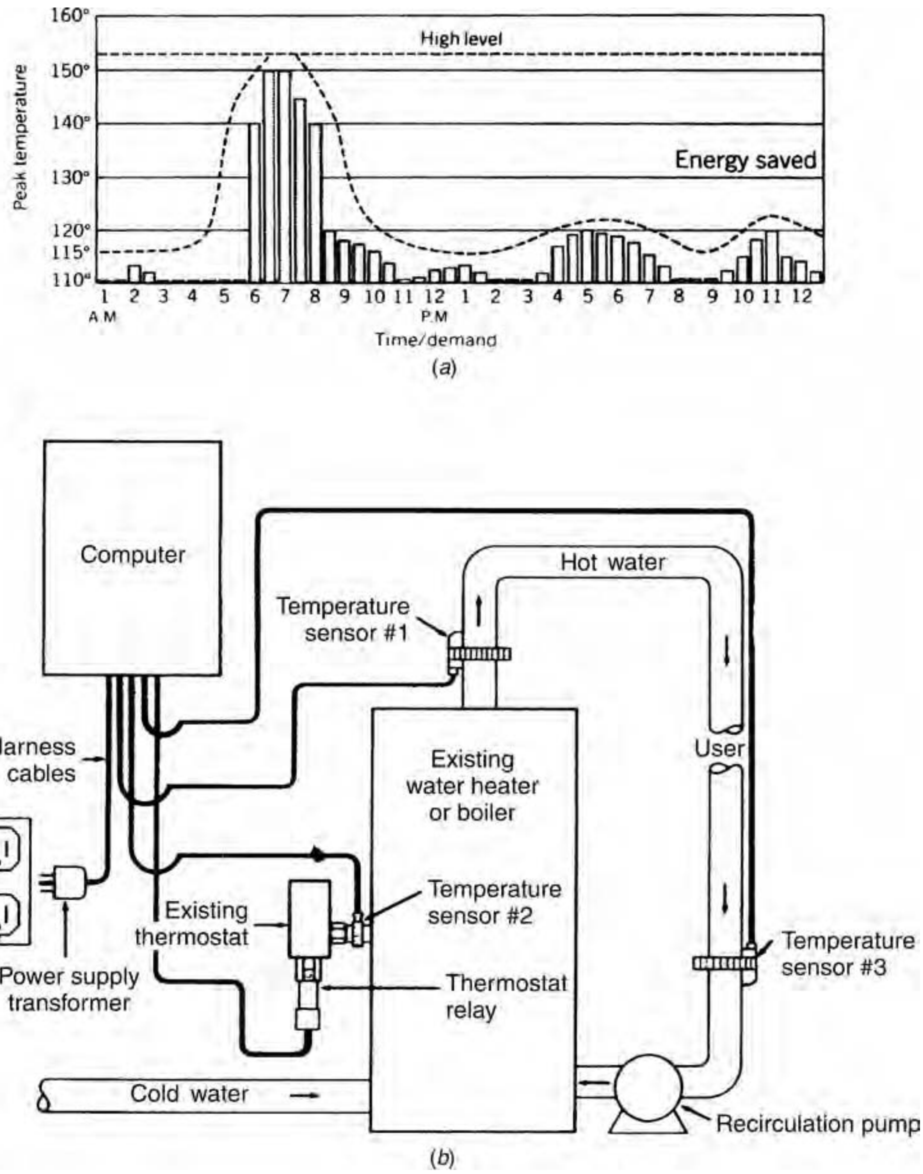


Fig. 19.21 *Variable temperature DHW supply. (a) Energy savings are possible when the supply temperature of hot water is varied. Heat losses from supply pipes are greatly reduced for most of the typical day. A computer controls the supply temperature. (b) Schematic of computer-controlled, variable-temperature DHW system. (Courtesy of Fluidmaster, Inc., Anaheim, CA.)*

energy-conserving model of which is shown in Fig. 19.22.

For residences, the capacity of hot water heating/storage equipment can be taken from the values in Table 19.8. Note that for the familiar tank-type direct water heaters (gas, electric, or oil), there is a stated relationship among storage size, rate of hourly heat input, rate of draw (demand) over 1 hour, and recovery rate. Example 19.2 uses Table 19.8 for the sizing of a residential water heater.

EXAMPLE 19.2 Select a natural gas water heater for a five-bedroom house with three baths. The *minimum* requirements of HUD-FHA are shown in Table 19.8: 50 gal (190 L), 47,000 Btu/h (1.38 kW), 90 gal (340 L) draw per hour, and 40 gph (151 L/h) recovery.

SOLUTION

From Fig. 19.22 and Table 19.9, a model BTH 120 is selected; it exceeds all the minimums. ■

Cyclone XHE Data:

[All models are 27¾ × 30 in. (705 × 762 mm) with 3-in. (76-mm) PVC vents]

Model	Storage Capacity, gal (L)	Btuh Input/Output	Recovery (gal/h) at 94% Thermal Efficiency		Height	
			80F° Δt	100F° Δt	in.	mm
BTH-120	60 (227)	120,000/112,800	171	137	55½	(1410)
BTH-150	100 (378)	150,000/141,000	214	171	74½	(1892)

Fig. 19.22 *"Cyclone XHE" water-heater storage tank using natural gas (or propane). This model achieves 94% thermal efficiency with a burner located at the top, forcing blower-driven air into a countercurrent contact with rising fuel. A precise mix of air and fuel at the point of ignition results in high combustion efficiency, and the swirling flame continues downward in a submerged central combustion chamber. The heated gas is then forced at high velocity through the spiral heat-exchanger coil, with a swirling action that maximizes heat exchange with the water. (Courtesy of the A.O. Smith Water Products Company, Irving, TX.)*

Estimation of the hot water demand for commercial and institutional buildings is not so simple, and design guidelines are less reliable. For larger buildings, there is a trade-off between quick recovery (high heating capacity) and storage size. Another variable is storage temperature, as discussed earlier in Section 19.6*a.*

Small shops and very small office buildings can be treated like residences for hot water sizing. For larger buildings, the trade-off between heaters and storage tanks should be explored. To begin this process, consult Table 19.10, which shows the maximum hourly and daily demands and contrasts them to an average day (which should be used to estimate monthly energy consumption).

The relationship between heater size and tank size is graphed in Fig. 19.23. The advantage of a *larger heater* is its smaller tank, which consumes less space and volume, weighs less, and probably has a lower first cost. The advantage of a *larger tank* is that its smaller heater tends to work steadily rather than in spurts; this lower, steadier demand for energy will lead to lower utility rates in the case of electric heating and thus to money savings over the life of

TABLE 19.8 HUD-FHA Minimum Water Heater Capacities, Residential

PART A. I-P UNITS											
Number of Bedrooms	**1**	**2**	**3**	**2**	**3**	**4**	**5**	**3**	**4**	**5**	**6**
Number of Baths		***1–1.5***			***2–2.5***				***3–3.5***		
Gas[a]											
Storage, gal	20	30	30	30	40	40	50	40	50	50	50
Input, 1000 Btu/h	27	36	36	36	36	38	47	38	38	47	50
1-h draw, gal	43	60	60	60	70	72	90	72	82	90	92
Recovery, gph	23	30	30	30	30	32	40	32	32	40	42
Electric[a]											
Storage, gal	20	30	40	40	50	50	66	50	66	66	80
Input, kW	2.5	3.5	4.5	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
1-h draw, gal	30	44	58	58	72	72	88	72	88	88	102
Recovery, gph	10	14	18	18	22	22	22	22	22	22	22
Oil[a]											
Storage, gal	30	30	30	30	30	30	30	30	30	30	30
Input, kW	70	70	70	70	70	70	70	70	70	70	70
1-h draw, gal	89	89	89	89	89	89	89	89	89	89	89
Recovery, gph	59	59	59	59	59	59	59	59	59	59	59
Tank-type indirect[b, c]											
I-W-H-rated draw, gal in 3 h, 100F° rise		40	66		66	66[e]	66	66	66	66	66
Manufacturer-rated draw, gal in 3 h, 100F° rise		49	49		75	75[e]	75	75	75	75	75
Tank capacity, gal		66	66		66	66[e]	83	66	82	82	82
Tankless-type indirect[c, d]											
I-W-H-rated draw, gpm, 100F° rise		2.75	2.75		3.25	3.25[e]	3.75	3.75	3.75	3.75	3.75
Manufacturer-rated draw, gal in 5 min, 100F° rise		15	15		25	25[e]	35	25	35	35	35
PART B. SI UNITS											
Gas[a]											
Storage, L	76	114	114	114	150	150	190	150	190	190	190
Input, kW	7.9	10.5	10.5	10.5	10.5	11.1	13.8	11.1	11.1	13.8	14.6
1-h draw, L	163	227	227	227	265	273	341	273	311	341	350
Recovery, mL/s	24	32	32	32	32	36	42	34	34	42	44
Electric[a]											
Storage, L	76	114	150	150	190	190	250	190	250	250	300
Input, kW	2.5	3.5	4.5	4.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
1-h draw, L	114	167	220	220	273	273	334	273	334	334	387
Recovery, mL/s	10	15	19	19	23	23	23	23	23	23	23
Oil[a]											
Storage, L	114	114	114	114	114	114	114	114	114	114	114
Input, kW	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1-h draw, L	337	337	337	337	337	337	337	337	337	337	337
Recovery, mL/s	62	62	62	62	62	62	62	62	62	62	62
Tank-type indirect[f, g]											
I-W-H-rated draw, L in 3 h, 55 K rise		150	150		250	250[e]	250	250	250	250	250
Manufacturer-rated draw, L in 3 h, 55 K		186	186		284	284[e]	284	284	284	284	284
Tank capacity, L		250	250		250	250[e]	310	250	310	310	310
Tankless-type indirect[g, h]											
I-W-H-rated draw, mL/s, 55 K rise		170	170		200	200[e]	240	200	240	240	240
Manufacturer-rated draw, L in 5 min, 55 K rise		57	57		95	95[e]	133	95	133	133	133

Source: Reprinted with permission; ©ASHRAE, 2011 *ASHRAE Handbook—HVAC Applications*.

[a]Storage capacity, input, and recovery requirements are typical and may vary with individual manufacturers. Any combination of these requirements to produce the stated 1-hour draw will be satisfactory.

[b]Boiler-connected water heater capacities (180°F boiler water, internal, or external connection).

[c]Heater capacities and inputs are the minimum allowable. Variations in tank size are permitted when recovery is based on 4 gph/kW at 100F° rise for electrical, AGA recovery ratings for gas, and IBR ratings for steam and hot water heaters.

[d]Boiler-connected heater capacities (200°F boiler water, internal, or external connection).

[e]Also for 1.5 baths and 4 bedrooms for indirect water heaters.

[f]Boiler-connected water heater capacities (82°C boiler water, internal, or external connection).

[g]Heater capacities and inputs are the minimum allowable. Variations in tank size are permitted when recovery is based on 4.2 mL/s kW at 55C° rise for electrical, AGA recovery ratings for gas, and IBR ratings for steam and hot water heaters.

[h]Boiler-connected heater capacities (93°C boiler water, internal, or external connection).

TABLE 19.9 Procedure for Sizing a Residential Water-Heater Storage Tank

	Table 19.8: *HUD-FHA*	*Fig. 19.22 Data: Cyclone XHE*
Characteristic	**5 Bedrooms, 3 Baths**	**Model BTH-120**
Storage, gal (L)	50 (190)	60 (227)
Input, Btu/h (kW)	47,000 (13.8)	120,000 (35.2)
1-h draw (= tank capacity + 1-hr recovery)	90 (340)	231 at 80F° (875 at 44 C°)
Recovery	40 (150)	171 (650)

the system. When the heat source is solar energy or waste heat, a larger tank is usually best suited to the characteristics of the energy supply.

EXAMPLE 19.3 A women's dormitory housing 300 students, with a cafeteria serving 300 meals in 1 hour, is to be built. Find the required hot water storage size for two conditions: (1) assuming a minimum recovery rate for both dorm and cafeteria and (2) assuming a dorm recovery rate of 2.5 gph (9.5 L/h), which is half of the maximum hourly value given in Table 19.10, and a cafeteria recovery rate of 1.0 gph (3.8 L/h), which is two-thirds of the maximum hourly value given in Table 19.10.

SOLUTION

Minimum Recovery:

From Fig. 19.23*a*, the minimum recovery rate for women's dormitories is 1.1 gph (4.2 L/h). For 300 students,

$$300 \times 1.1 = 330 \text{ gph } (300 \times 4.2 = 1260 \text{ L/h}) \text{ recovery}$$

At this rate, again from Fig. 19.23*a*, the minimum usable storage capacity is 12 gal/student (45 L/student). Assume that 70% of the total capacity is usable capacity. This means that after 70% of the stored hot water is withdrawn, the remaining water has been cooled (by incoming water) to an unusably low temperature. Storage size must be increased by

$$\frac{100\%}{70\%} = 1.43$$

TABLE 19.10 Domestic Hot Water, Commercial/Institutional

Type of Building	Maximum Hour	Maximum Day	Average Day
Men's dormitories	3.8 gal (14.4 L)/student	22.0 gal (83.4 L)/student	13.1 gal (49.7 L)/student
Women's dormitories	5.0 gal (19 L)/student	26.5 gal (100 L)/student	12.3 gal (46.6 L)/student
Motels: no. of units[a]			
20 or less	6.0 gal (23 L)/unit	35.0 gal (132.6 L)/unit	20.0 gal (75.8 L)/unit
60	5.0 gal (20 L)/unit	25.0 gal (94.8 L)/unit	14.0 gal (53.1 L)/unit
100 or more	4.0 gal (15 L)/unit	15.0 gal (56.8 L)/unit	10.0 gal (37.9 L)/unit
Nursing homes	4.5 gal (17 L)/bed	30.0 (114 L)/bed	18.4 gal (69.7 L)/bed
Office buildings	0.4 gal (1.5 L)/person	2.0 gal (7.6 L)/person	1.0 gal (3.8 L)/person
Food service establishments:			
Type A—full meal restaurants and cafeterias	1.5 gal (5.7 L)/max meals/h	11.0 gal (41.7 L)/max meals/h	2.4 gal (9.1 L)/avg meals/day[b]
Type B—drive-ins, grilles, luncheonettes, sandwich and snack shops	0.7 gal (2.6 L)/max meals/h	6.0 gal (22.7 L)/max meals/h	0.7 gal (2.6 L)/avg meals/day[b]
Apartment houses: no. of apartments			
20 or less	12.0 gal (45.5 L)/apt.	80.0 gal (303.2 L)/apt.	42.0 gal (159.2 L)/apt.
50	10.0 gal (37.9 L)/apt.	73.0 gal (276.7 L)/apt.	40.0 gal (151.6 L)/apt.
75	8.5 gal (32.2 L)/apt.	66.0 gal (250 L)/apt.	38.0 gal (144 L)/apt.
100	7.0 gal (26.5 L)/apt.	60.0 gal (227.4 L)/apt.	37.0 gal (140.2 L)/apt.
200 or more	5.0 gal (19 L)	50.0 gal (195 L)/apt.	35.0 gal (132.7 L)/apt.
Elementary schools	0.6 gal (2.3 L)/student	1.5 gal (5.7 L)/student	0.6 gal (2.3 L)/student[b]
Junior and senior high schools	1.0 gal (3.8 L)/student	3.6 gal (13.6 L)/student	1.8 gal (6.8 L)/student[b]

Source: Reprinted with permission; ©ASHRAE, 2011 *ASHRAE Handbook—HVAC Applications*.

[a]Interpolate for intermediate values.

[b]Per day of operation.

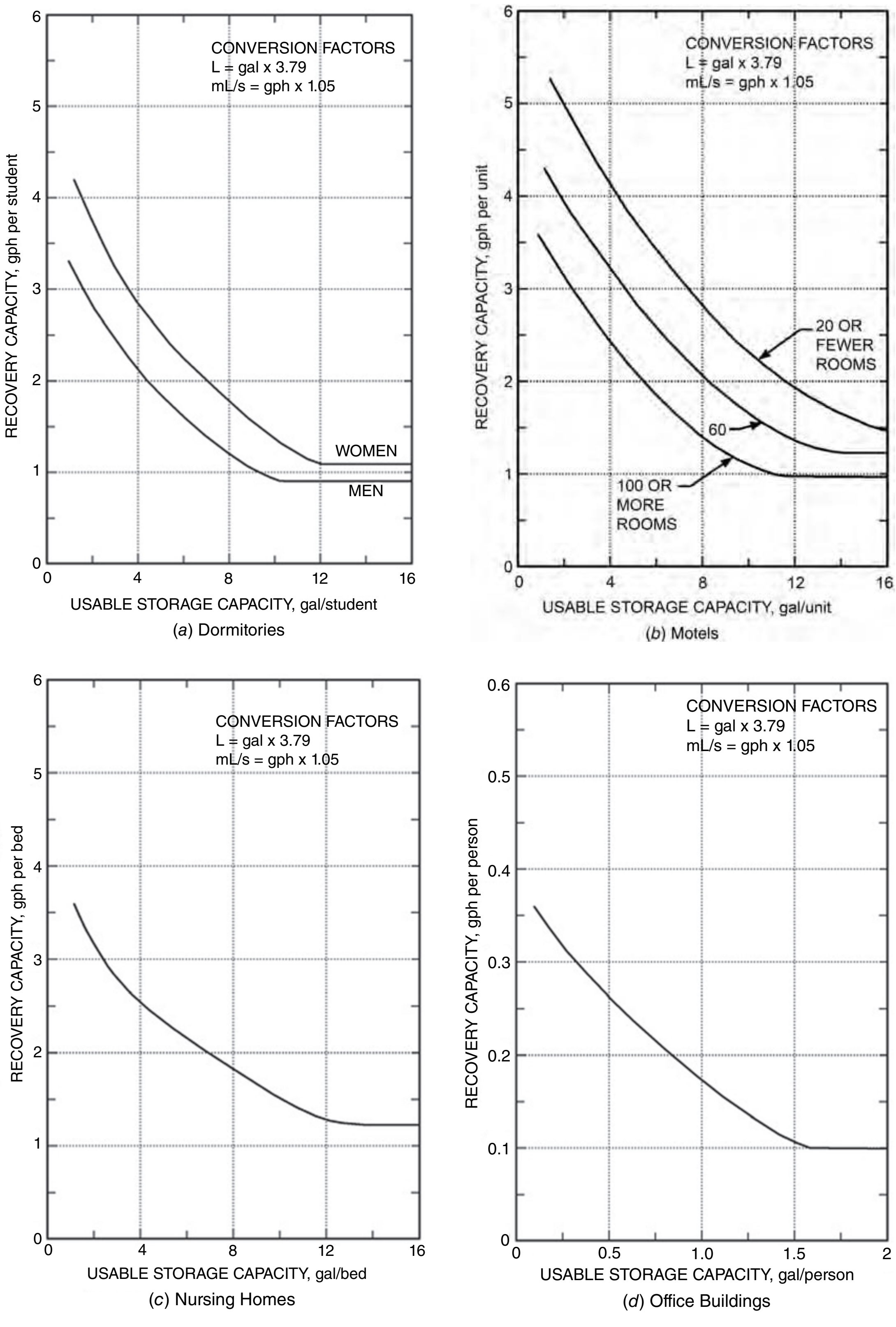
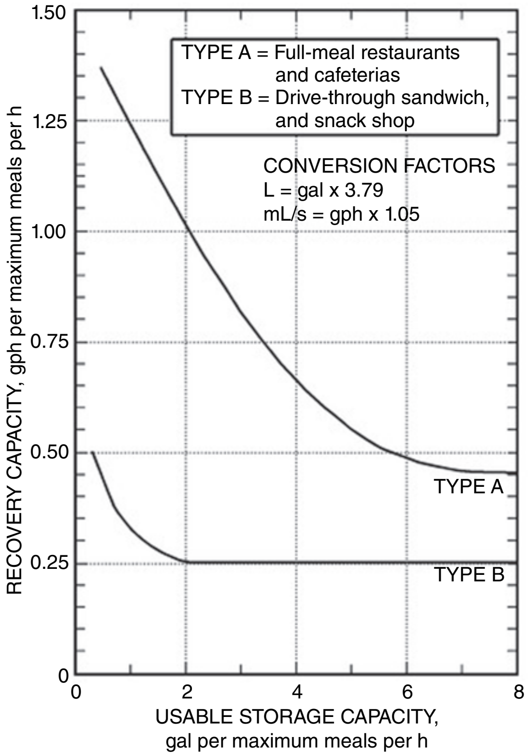
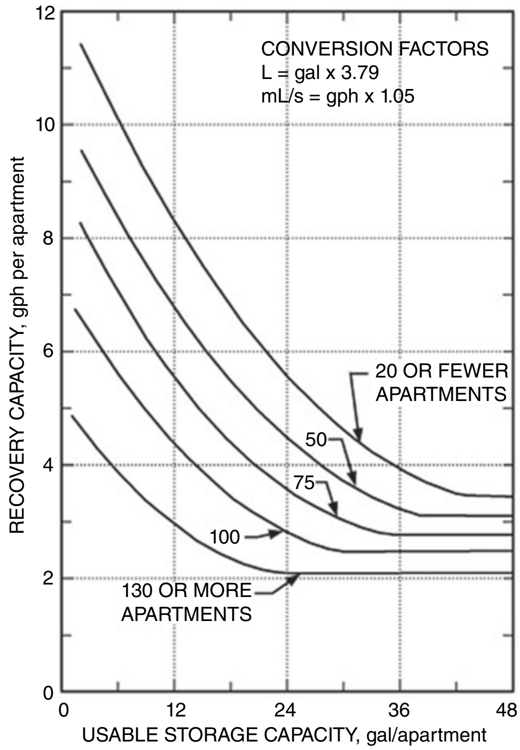


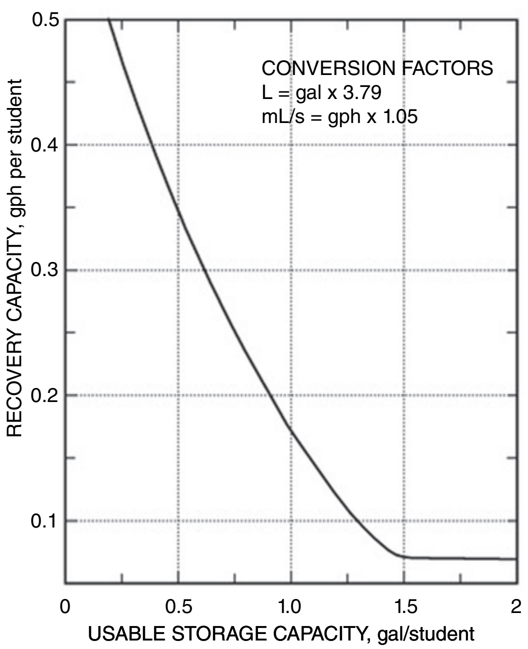
Fig. 19.23 *Domestic hot water sizing; the trade-off between recovery (heater) capacity and storage capacity. Usable storage capacity is usually considered to be between 60% and 80% of the total tank capacity. For (b) Motels, and (f) Apartments, curves are based upon the number of dwelling units. For (e) Food service, Types A, B, see Table 19.10. (Reprinted with permission; ©ASHRAE, 2011* ASHRAE Handbook—HVAC Applications.*)*



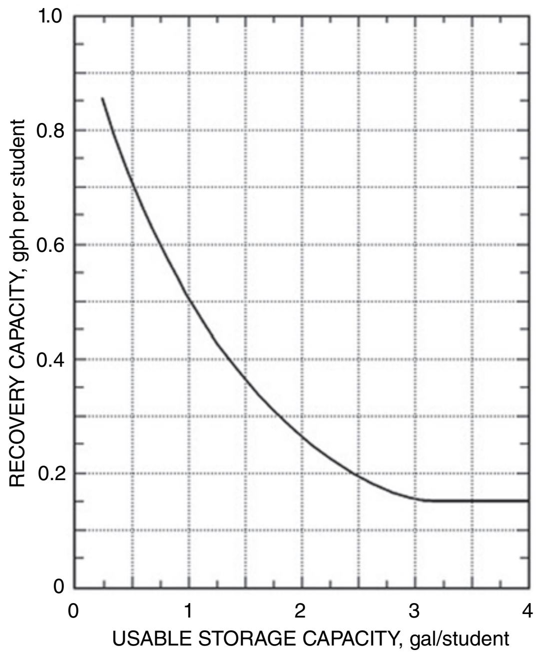
(*e*) Food Service



(*f*) Apartments



(*g*) Elementary Schools



(*h*) High Schools

Fig. 19.23 *(Continued)*

Thus

$$12 \times 300 \times 1.43 = 5150 \text{ gal}$$
$$(45 \times 300 \times 1.43 = 19{,}300 \text{ L}) \text{ storage}$$

From Fig. 19.23*e*, the minimum recovery rate for the cafeteria (serving full meals, type A) is 0.45 gph (1.7 L/h). For 300 meals,

$$300 \times 0.45 = 135 \text{ gph}$$
$$(300 \times 1.7 = 510 \text{ L/h}) \text{ recovery}$$

At this rate, the minimum usable storage capacity is 7 gal/meal (26.5 L/meal). Thus

$$300 \times 7 \times 1.43 = 3000 \text{ gal}$$
$$(300 \times 26.5 \times 1.43 = 11{,}370 \text{ L}) \text{ storage}$$

Combining these requirements for dorm and cafeteria,

$$\text{recovery} = 330 + 135 = 465 \text{ gph}$$
$$(1260 + 510 = 1770 \text{ L/h})$$

$$\text{storage} = 5150 + 3000 = 8150 \text{ gal}$$
$$(19{,}300 + 11{,}370 = 30{,}670 \text{ L})$$

Faster Recovery:
At the specified dorm recovery rate of 2.5 gph (9.5 L/h),

$$300 \times 2.5 = 750 \text{ gph}$$
$$(300 \times 9.5 = 2850 \text{ L/h})$$

and the minimum usable storage required is 5 gal/student (18.9 L/student). Thus

$$300 \times 5 \times 1.43 = 2150 \text{ gal}$$
$$(300 \times 18.9 \times 1.43 = 8110 \text{ L})$$

At the specified cafeteria recovery rate of 1.0 gph (3.8 L/h),

$$300 \times 1.0 = 300 \text{ gph}$$
$$(300 \times 3.8 = 1140 \text{ L/h})$$

and the minimum usable storage required is 2 gal/meal (7.6 L/meal). Thus

$$300 \times 2.0 \times 1.43 = 860 \text{ gal}$$
$$(300 \times 7.6 \times 1.43 = 3260 \text{ L})$$

Combining these requirements for dorm and cafeteria,

$$\text{recovery} = 750 + 300 = 1050 \text{ gph}$$
$$(2850 + 1140 = 3990 \text{ L/h})$$

$$\text{storage} = 2150 + 860 = 3010 \text{ gal}$$
$$(8110 + 3260 = 11{,}370 \text{ L})$$

For this example, an increase in heater size of 225% for faster recovery allows the size of the tank to be reduced to only 37% of original size.

Note: This sizing procedure does not account for *system losses*, that is, heat lost from the storage tanks and from the hot water piping. Recovery capacities are usually increased because of these losses, which are simple to calculate when the U-factors of the tank and pipe insulation are known: Btu/h = $U \times A \times \Delta t$. ■

For these larger DHW applications, central steam is often used as a heat source. Figure 19.24 shows an indirect storage tank system. Such systems may cost more than tankless systems, but they are usually cheaper to operate, both because the

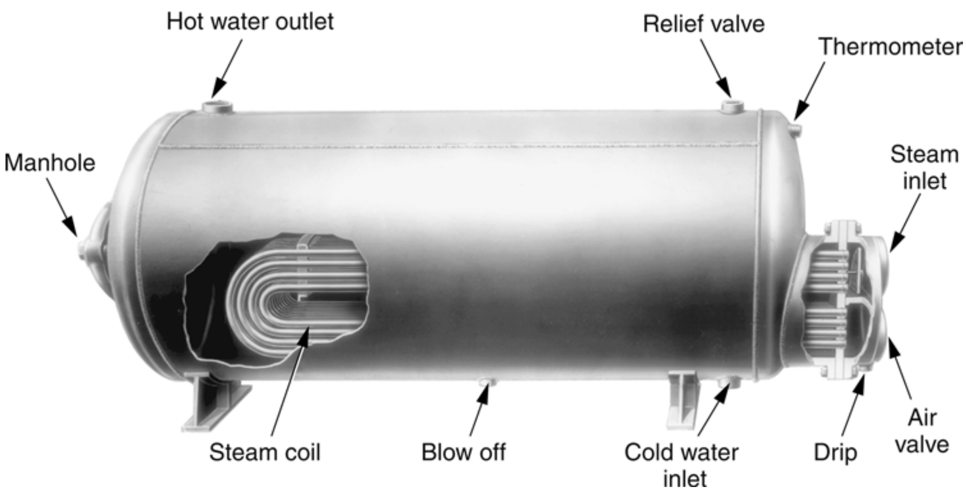


Fig. 19.24 *Storage tank and heater for DHW for large-demand applications. A steam coil is submerged in the tank. Capacities from 100 to 10,000 gph (380 to 37,850 L/h), varying by length of coil, for a 140F° (78C°) temperature rise (from 40° to 180°F [4 to 82°C]).*

peak prices for the instantaneous fuel demands of tankless heaters are avoided and because low-grade steam or waste high-temperature water sources can be utilized.

In any system that heats water under pressure, safety precautions are necessary. To minimize the dangers of excessive pressure (which can damage the system) and of superheated water (which can severely injure people), most codes require *pressure and temperature* (*P/T*) *relief valves* to be installed on top of all water heaters. Because these valves are designed to release hot water whenever a dangerous pressure or temperature is reached, they should be attached to a length of pipe that will conduct the released water to a drain.

(i) Solar Water Heating

Solar energy is most attractive to a designer when it will do most of its work during the time that it is most available. On a seasonal basis (Fig. 19.25), solar energy is especially attractive for outdoor swimming pool heating, as it will be used only in sunny, warm months. Throughout the United States, solar energy can easily meet most of the summertime demand for DHW as well. In the northern part of the country, a much smaller solar contribution can be expected in winter. An especially difficult problem is the winter space-heat mismatch between greatest need and least solar energy supply. For both solar DHW and space-heating systems, winter brings the added complication of the need to protect water in collectors against freezing.

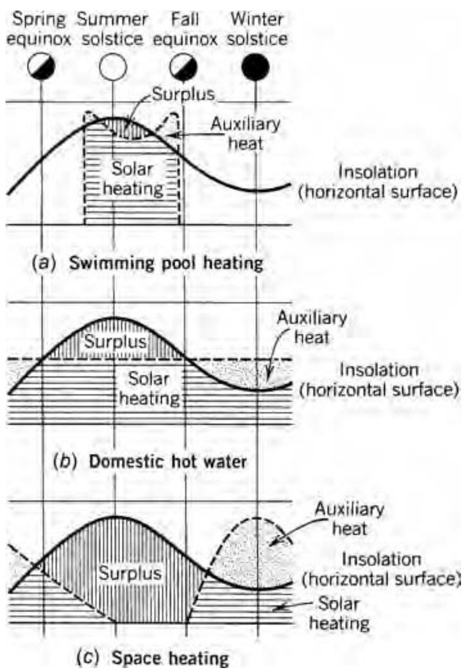


Fig. 19.25 *Comparison of the pattern of solar energy supply (on a horizontal surface) to various patterns of heating needs.*

Again, there are many ways in which solar energy can be used to heat water. Solar water-heating systems are usually classified by the means of fluid circulation (passive or active), the means by which heat from the collector piping is transferred to the DHW itself (direct, indirect, or closed-loop), and the means of protection against freezing.

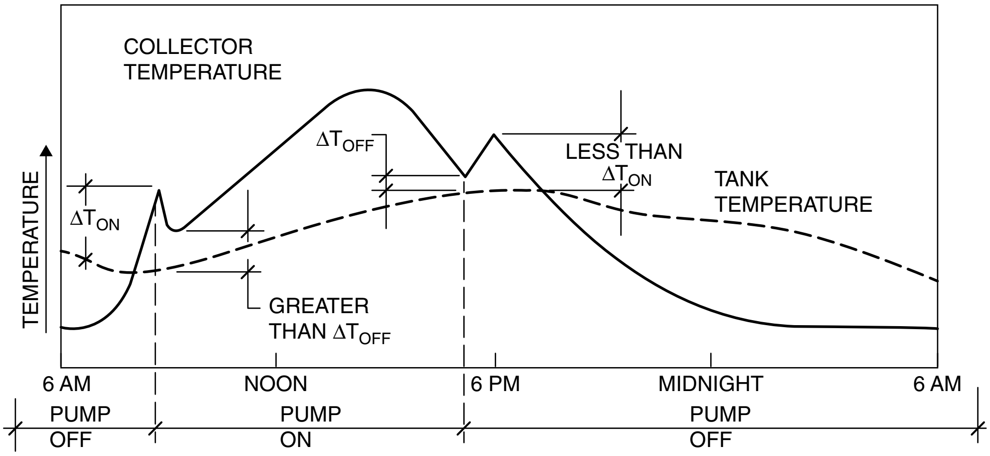
Passive systems rely upon gravity for circulation, as explained in Section 19.6*f*. Hence, the storage tank usually must be placed *above* the collector (Fig. 19.26), and the number of bends in the system supply and return piping must be minimized to reduce friction. Heavy storage tanks located high in a building can cause structural problems. The advantages of this passive approach include lower cost of components, high mechanical reliability (no pump, etc.), and low operational costs.

Active systems use pumps to force the fluid into the collector. Although this setup allows the collector and storage to be located anywhere that is convenient for the designer, it introduces the complications of mechanical breakdown, increased maintenance, and the cost of the energy needed to run the pump. Active DHW systems are widespread in North America; see Figs. 19.27 and 19.28 for typical systems.

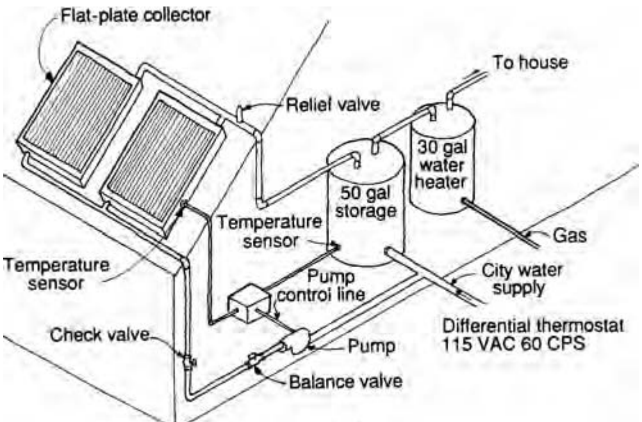
Direct systems utilize only one fluid: The water to be heated for use in the building is circulated through the solar collector. Such a system has the advantages of simplicity and efficiency, as it does not require a separate fluid loop and the attendant piping complications and inefficiencies of heat exchange.

Indirect systems use a closed loop containing a fluid that circulates through the collector and storage tank. The fluid is not mixed with the DHW itself; rather, heat is passed from one fluid to the other through a heat exchanger. One advantage of this system is that it allows nonfreezing solutions to be used in the collector loop. It also allows collectors to

Fig. 19.26 *Solar water heaters are widely used. This house in Miami, Florida, incorporates a storage tank above the collector, which is enclosed in the chimney-like form. This permits passive (thermosiphon) circulation without a pump. (Photo by M. Steven Baker.)*

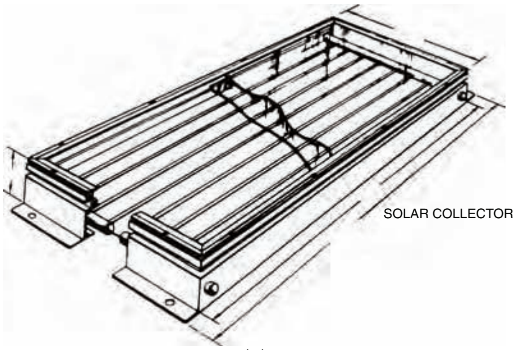


(*a*)

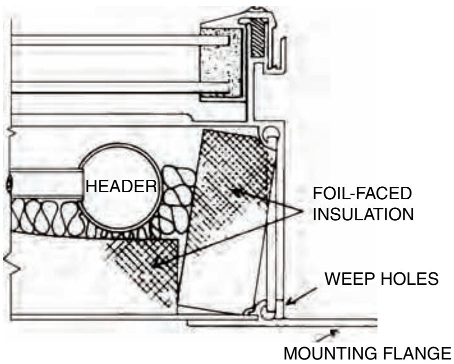


(*b*)

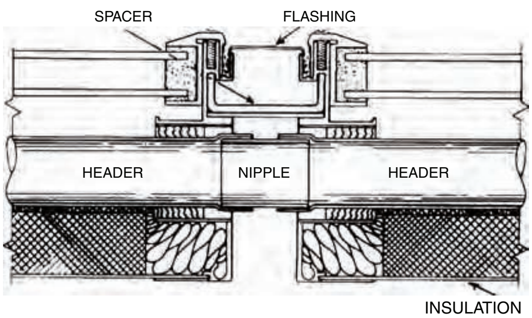
Fig. 19.27 *Active solar water heating utilizes differential controllers (a) that compare the collector temperature to that of the storage tank. (b) Typical DHW system with separate solar and conventional heater tanks. (The alternative of only one storage tank produces less standby heat loss, but may reduce solar collection by feeding the collector with gas-heated water.)*



(*a*)



(*b*)



(*c*)

Fig. 19.28 *(a) Cutaway section of a typical active solar collector. (b) Cross section at the header. (c) Method of connecting manifolds of adjacent solar collectors.*

be operated at low pressure rather than at the high pressures typical of urban public water systems. The choice of fluid is determined by its freezing and boiling points, its specific heat, and its level of toxicity.

As Table 19.11 shows, these design elements (passive and active, direct and indirect) are combined in a number of typical solar DHW systems. Brief descriptions of some of the more common systems follow.

1. *Batch systems.* In these, the simplest of all such systems, a black-painted storage tank is exposed to the sun within a glazed collector box (Fig. 19.29). The price of simplicity is the inefficiency of exposing a tank of hot water to the cold nighttime conditions of the collector. Movable insulation, however inconvenient, can be used to reduce this problem. These heaters are also referred to as *breadbox* water heaters and *integral passive solar water heaters*. The batch system was used at the Antelope Valley California Poppy Reserve (Fig. 10.32), as shown in Fig. 19.30. Because of their simplicity, they are favored by do-it-yourself builders, especially in mild winter climates.

A more recent batch collector design utilizes eight copper tubes in a well-insulated, double-glazed (glass out, Teflon in) frame. The water flows in series, allowing the colder replacement water to enter at the bottom of the collector, with the hottest water at the top, ready for use. Insulation between the tubes helps maintain this temperature difference. Collectors are available in storage sizes of approximately 30, 35, 40, and 50 gal, weighing when filled 425 to 664 lb (114, 133, 152, and 190 L, weighing 193 to 301 kg).

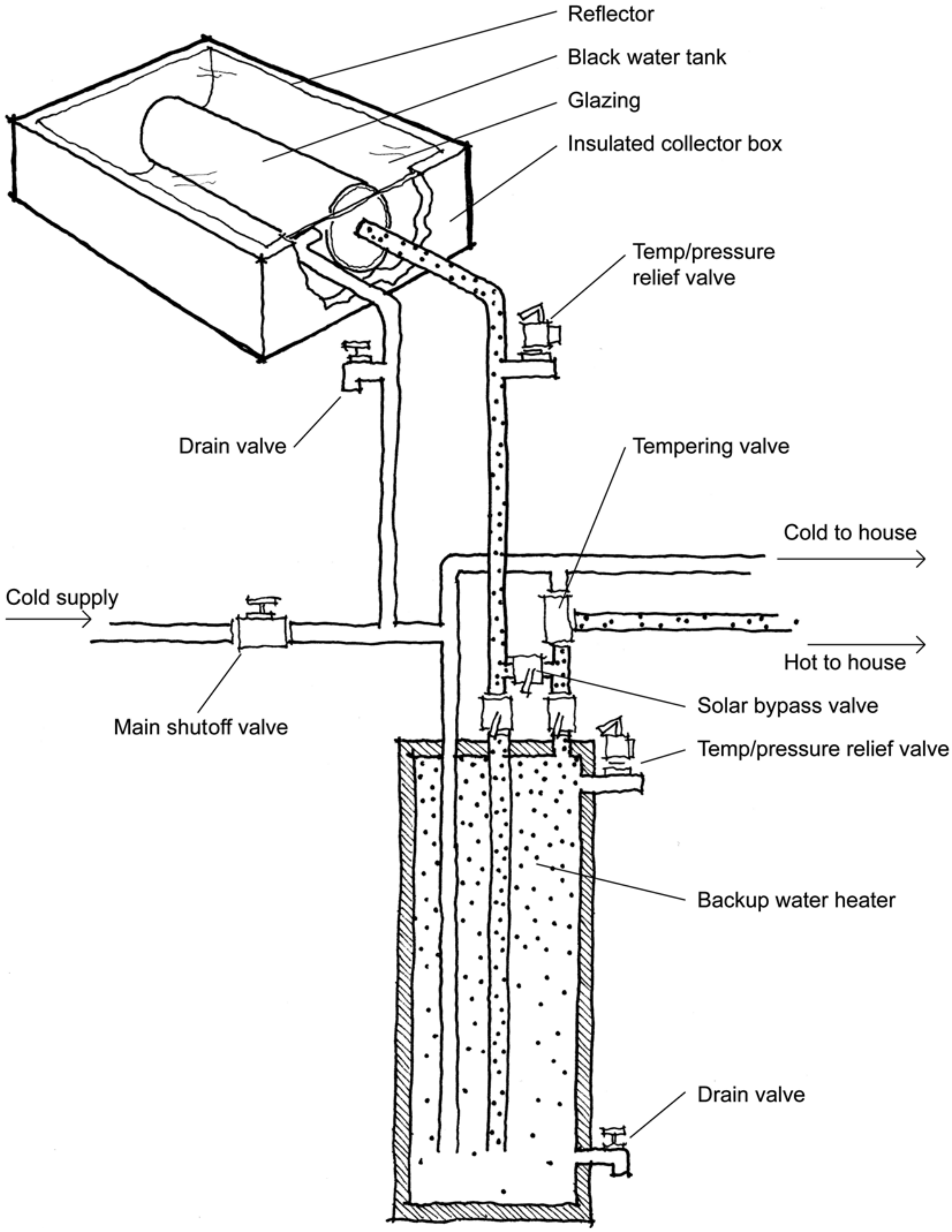
2. *Thermosiphon systems.* The sun acts as both the pump and the heat source for these systems (Fig. 19.31). With no moving parts, maintenance needs are low. The collector, however, must be lower than the tank, and piping must be kept as simple as possible. Because the coldest water remains in the lower collector at night, the hot water in the upper tank is not threatened with undue heat loss. However, freezing conditions pose a severe threat to the collector. Accordingly, indirect (closed-loop) systems containing a nonfreezing fluid are frequently used; *phase-change systems* are a promising cold-winter option for this type of passive system.

TABLE 19.11 Solar Domestic Hot Water Systems

Type	Main Features	Advantages	Disadvantages
Batch system	Batch tank inside collector box. Potable water within collector/tank.	No external power. Few components. Collector/tank at any location.	Seasonal; dependent on freezing locations. Heat loss at night from storage.
Thermosiphon system	Flat-plate liquid collectors. Normally open loop but no pump or external power passive (DHW system). Storage tank higher than collector.	No external power. Few components. High performance.	Seasonal; dependent on freezing locations (if water is collector fluid). Needs structural support for high storage tank.
Geyser pumping system	Flat-plate liquid collectors. Methanol-water solution passively pumped by solar heat to a heat exchanger below.	No freezing damage. No mechanical or electric parts. No liquid service.	Temporarily stops operation at subzero temperatures, as solution freezes to a slush.
Closed-loop freeze-resistant system	Flat-plate liquid collectors. Closed loop of piping from collectors to storage tank. Uses external energy (circulator and differential controller). Uses nonfreezing collector fluid. Pressurized stonelined storage tank.	Can be used in coldest climates. More and better-established competition. Circulator; small consumption of external energy. High performance.	Liquid; service/maintenance required. More components required.
Drain-back system	Flat-plate liquid collectors. Water is collector fluid (open loop). Potable water circulates through the heat exchanger in the storage tank (not through the collectors). Large heat exchanger. Pitched headers.	Can be used in the coldest climates. No antifreeze used. Most simple of active flat-plate systems (no valves).	Larger pump; larger consumption of external energy. System must drain thoroughly. Use of corrosion inhibitor recommended.
Drain-down system	Flat-plate liquid collectors. Potable water circulated through collectors. Line pressure feeds collectors (open loop). Has automatic drainage valves. Pitched headers.	No heat exchanger or extra storage tank needed. High performance.	In some instances a larger pump; larger consumption of external energy. System must drain thoroughly. No corrosion inhibitor possible. Freeze danger with valve failure.
Air-to-liquid system	Flat-plate air collectors. Air-to-water heat exchanger. Ductwork and blower. Pipes and circulator. Larger collector area than liquid system.	Won't freeze (dependent on exchanger location). Air leaks won't cause damage. Integrates well with space heating.	Hard to detect leaks. More space required for ducts. Blower and circulator required. More carpentry involved. Less efficient than other systems.
Phase-change system	Flat-plate liquid collectors. Freon 114 or R12.[a] Storage tank higher than collectors (passive type). Closed-loop refrigerant-grade piping from collectors to storage tank (passive type) or to condenser (subambient type).	No external power (passive type). Can be mounted at any location (subambient type).	Very hard to detect leaks. Special equipment to install. More components required (subambient type).

Reprinted by permission from Russell H. Plante, *Solar Domestic Hot Water: A Practical Guide*, © 1983 by John Wiley & Sons. Information on the geyser pumping and batch systems added by the authors of this book.

[a]Environmentally-responsible refrigerants must be used in new systems.



Interactive Animation

Fig. 19.29 *Batch solar water-heating system. (Drawn by Dain Carlson; © Alison Kwok; all rights reserved.)*

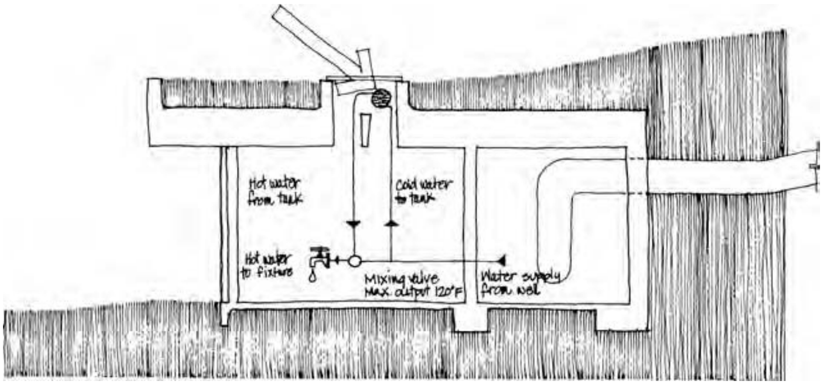


Fig. 19.30 *A batch solar water heater supplies the hot water for the Antelope Valley California Poppy Reserve. (Courtesy of the Colyer/Freeman Group, Architects, San Francisco.)*

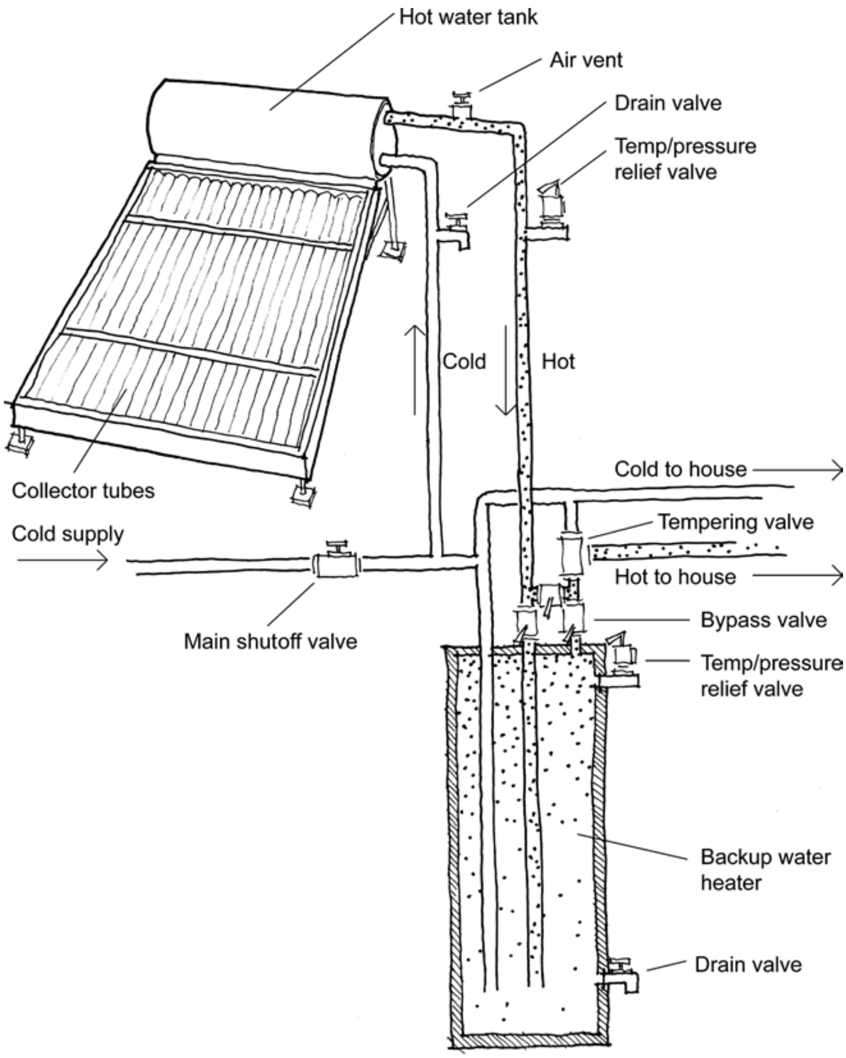


Fig. 19.31 *Thermosiphon solar water-heating system. (Drawn by Dain Carlson; © Alison Kwok; all rights reserved.)*

3. *Closed-loop, freeze-resistant systems.* In addition to being used in thermosiphoning arrangements, these systems are commonly used in active systems (Fig. 19.32). A small pump circulates nonfreezing fluid to the collector when there is sufficient sun. This process is governed by a differential controller. Alternatively, a PV-(photovoltaic) driven circulation pump can be used (see Fig. 30.16); when there is sufficient solar energy to activate the pump, there should be enough to also heat water in the collector.

The price of this freeze protection is the inefficiency of the heat exchanger, used between the collector fluid and the potable hot water. Some codes require a *double*-wall heat exchanger between any toxic nonfreezing fluid and the potable water, which further reduces efficiency.

4. *Drain-back systems.* Although these systems (Fig. 19.33*a*) use water as the fluid pumped from tank to collector, this water is not the potable hot water itself. Instead, the potable water passes through a heat exchanger in the solar storage tank. With the potable water kept out of the collector, the solar collector can operate at lower water pressure. This arrangement, however, requires a large heat exchanger, with attendant inefficiency. It also requires care in the design and installation of piping between the collector and tank so that the collector will drain thoroughly. When the controller senses that no solar energy can be gathered, it cuts off the pump, and water drains back into the tank. Therefore, the collector will be filled with air, not water, during all nighttime and cloudy-cold daytime hours. Corrosion inhibitors should be added to the collector/tank's water because the piping is frequently exposed to air.

5. *Drain-down systems.* These are the only active systems that do not utilize heat exchangers (Fig. 19.33*b*); DHW is circulated directly through the collector. Both higher pressure and higher efficiency result. In this system, the collector is usually filled with water that moves only when a differential controller activates the pump. Whenever the outside temperature drops near freezing, the controller activates solenoid valves and the water in the collector is drained down (dumped). In cold-winter areas, this process can result in several gallons of water wasted per winter day.

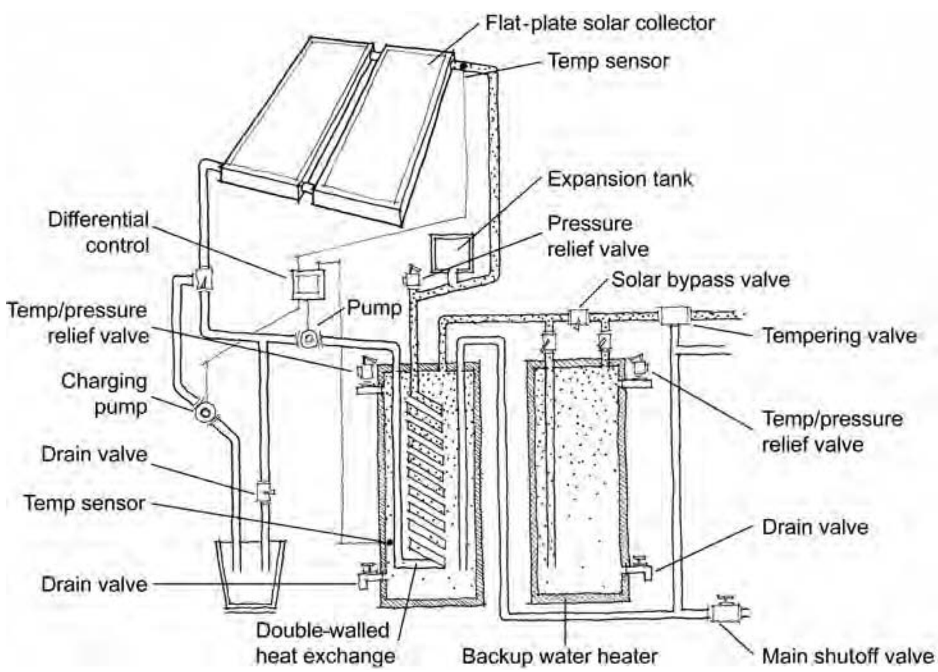


Fig. 19.32 Closed-loop, freeze-resistant solar water-heating system. (Drawn by Dain Carlson; © Alison Kwok; all rights reserved.)

Although the lack of a heat exchanger is attractive from the standpoint of cost savings and thermal efficiency, the set of electrically controlled solenoid valves is not foolproof. When malfunctions occur in pressurized systems, the loss of water can be enormous, and there is great potential for water damage to the building.

6. *Air-to-liquid systems.* These systems use air collectors and rock storage beds; a heat exchanger transfers heat from the collector-heated air to the hot water. Much lower efficiencies result, and the ductwork is much more space-consuming than are pipes for water collectors. Leaks in air collectors or storage beds are very difficult to detect. However, air collectors are not damaged by freezing.

7. *Phase-change systems.* In any of the aforementioned systems in which potable water is kept out of the collector, there are some missed opportunities—for instance, using the fluid within the collector as a mode of frost-resistance, taking advantage of the water's latent heat (the considerable amount of heat stored when fluid vaporizes and released when a fluid condenses), and so on. The primary disadvantages of a phase-change system (Fig. 19.34) are the high first cost, the difficulty in detecting leaks, and the resulting threat of chlorofluorocarbon or hydrochlorofluorocarbon refrigerant fluids to the environment.

Passive approaches to phase-change materials were outlined in the discussion of thermosiphoning systems. *Subambient* approaches utilize a heat pump

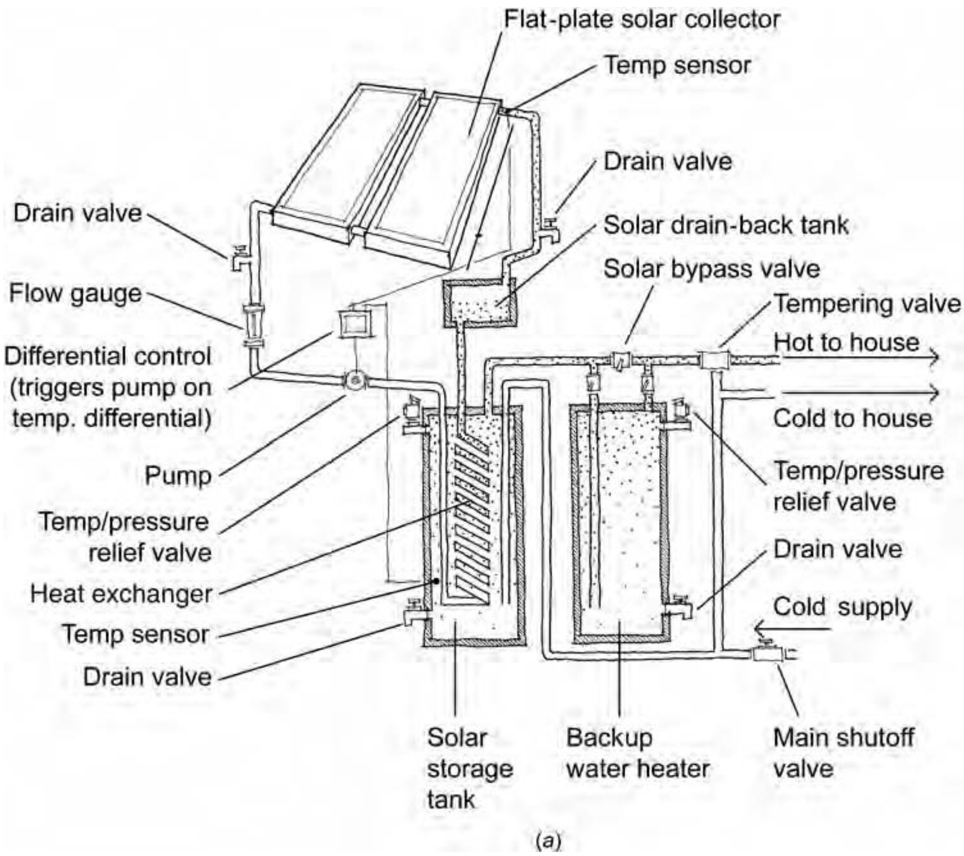


Fig. 19.33 *Comparison of (a) a drain-back solar water-heating system with (b) a drain-down system. The drain-back system's performance can be increased by the addition of a check valve that allows the colder water at the bottom of the storage tank to circulate into the heat exchanger. The drain-down system is best used in mild winter climates with infrequent freezing temperatures, since the water in the collector is dumped with each freezing threat. (Drawings by Dain Carlson; © Alison Kwok; all rights reserved.)*

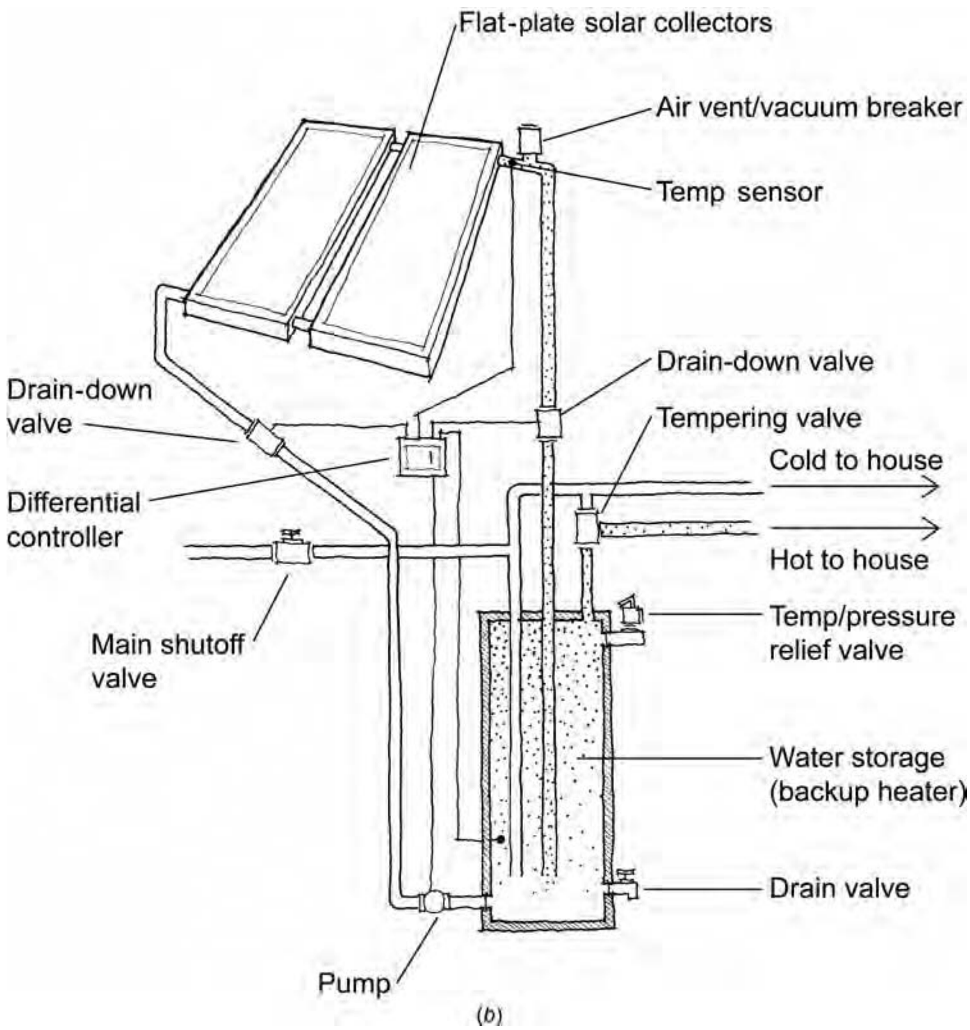


Fig. 19.33 *(Continued)*

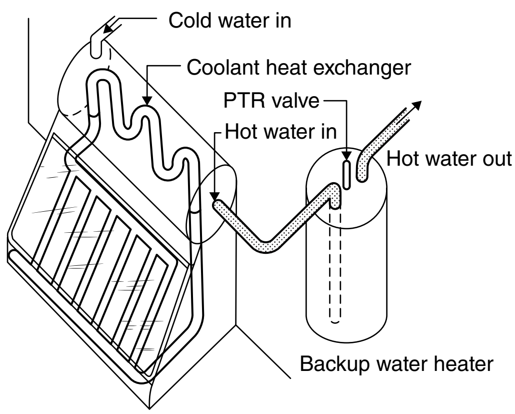


Fig. 19.34 *In a phase-change system, small heat exchangers can be built into the tops of thermosiphoning collectors; DHW is drained down when the threat of freezing arises. (Adapted by permission from* Solar Age*, November 1983.)*

and can glean heat even from cold-cloudy ("subambient") conditions. They thus represent a form of solar-assisted heat pump, closely related to those discussed in Section 19.6*j*.

The *sizing* of solar water heaters usually begins with simple design guidelines. For batch heaters, such a sizing guideline (Fig. 19.35) is:

0.45 to 0.65 ft^2 glazing per gallon of water stored
(0.011 to 0.016 m^2 per liter of water stored)

For the flat-plate solar collectors used in all the solar DHW systems listed in this section, the sizing guidelines are:

12 to 25 ft^2 collector/person (residential)
(1.1 to 2.3 m^2/person)
Optimum tilt (up from the horizontal) equal to latitude (or less)
1 to 1.5 gal of storage per square foot of collector area
(41 to 61 L per square meter of collector area)

This collector-sizing guideline is for *residential* hot water usage, including cooking and bathing. For warmer climates with ample insolation, use the lower figure; this will supply about half of the hot water on an annual average basis. (For *nonresidential* DHW, adjust the sizing guideline by comparing the gallons of hot water per person per day used in residences to those used in the nonresidential function under design.)

A more detailed sizing procedure would consider the collector's expected heat contribution for some typical months. Such a procedure requires both climate data and assumptions about water temperatures and other values. As a result, detailed answers are best obtained from computer programs, such as those listed in Appendix L. For those interested in something more than sizing guidelines but less than computer programs, consider the following approach to collector sizing (adapted from Brown, Reynolds, and Ubbelohde, *InsideOut: Design Procedures for Passive*

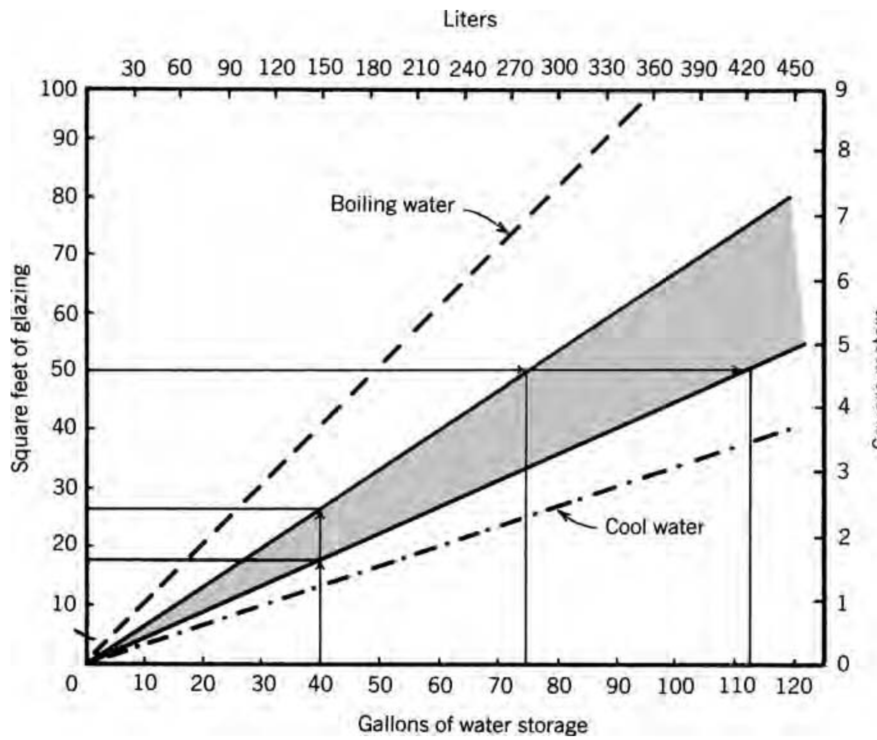


Fig. 19.35 *Design guideline for the sizing of batch solar water heaters. In this example, a 40-gal (150-L) storage tank should be contained within a collector that has between 18 and 27 ft^2 (1.7 and 2.5 m^2) of south-facing glazing. A 50-ft^2 (4.7-m^2) collector box should contain a tank of between 75 and 113 gal (285 and 430 L). (Adapted from Daniel K. Reif,* Passive Solar Water Heaters*; copyright © 1983 by Brick House Publishing Company, Inc. Reprinted by permission.)*

Environmental Technologies, © 1982 by John Wiley & Sons).

STEP 1. *Select the collector tilt angle.* This can be done by consulting Appendix C, Tables C.11 to C.14 for I-P (C.15 to C.18 for SI), which present clear-day insolation values for various tilt angles. Table C.19 for I-P (C.20 for SI) presents average insolation values on horizontal surfaces, which should also be checked. The tilt angle selected should be close to the optimum angle for the best month for total insolation.

STEP 2. *Check the collector efficiency.* This should be done at least twice: for the best insolation month and for the worst month. This step requires the following data:

Hourly insolation on tilted surface (Appendix C, Tables C.11 to C.14 for I-P [C.15 to C.18 for SI])

Outdoor average temperature (Appendix C, Table C.19 for I-P [C.20 for SI])

The hourly insolation values on tilted surfaces in Tables C.11 to C.14 (and C.15 to C.18) are for *clear* days. For most locations, this should be adjusted for *average* conditions, which are shown for vertical (south) and horizontal surfaces in Table C.19 (and C.20). Because for most of North America the optimum yearly DHW tilt angle will be closer to horizontal than to vertical, a simple correction to insolation must be made:

Hourly average day insolation on tilted surface

$$= \begin{bmatrix} \text{hourly clear-day} \\ \text{insolation on} \\ \text{tilted surface} \end{bmatrix} \times \begin{bmatrix} \dfrac{\text{average-day total horizontal insolation}}{\text{clear-day total horizontal insolation}} \end{bmatrix}$$

This step also requires assumptions about the input temperature of the water supplied to the collector (T_i). In summer, this can be quite high—even higher than the thermostat setpoint temperature of the hot water tank. In winter, it is likely to be lower, by perhaps 10 to 20F° (5.5 to 11C°), than the thermostat setpoint temperature. Finally, this step requires a choice of collector type so that efficiency can be determined. Figure 19.36 shows the efficiency curves for a variety of solar collectors.

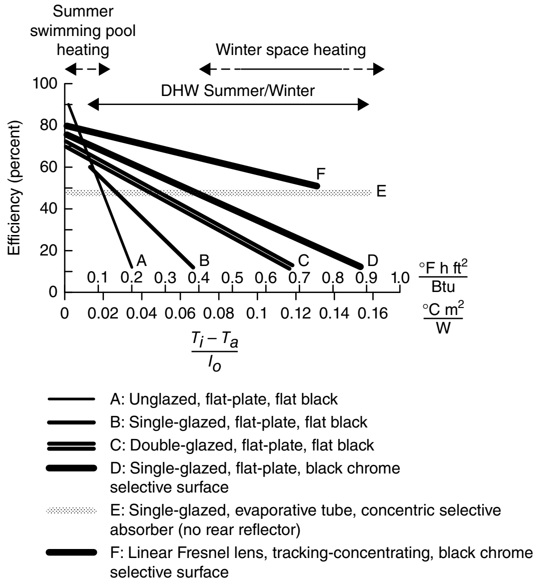


Fig. 19.36 *Collector efficiencies depend upon insolation (I_o), water temperature entering the collector (T_i), and ambient (air) temperature (T_a). (Based on the U.S. Dept. of Housing and Urban Development's* Intermediate Minimum Property Standards Supplement*, 1977.)*

Note that the simplest of all, the unglazed flat black collectors, have the highest efficiency of all collectors at combinations of very low $T_i - T_a$ and very high I_o. These conditions are typical of summer days, on which the water needs to be heated only a few degrees. This corresponds to swimming pool applications and is one reason such collectors are so popular for that purpose; low cost is another reason.

For the opposite conditions—those of winter space heating—more elaborate collectors are appropriate. Evacuated-tube collectors have the advantage of nearly eliminating collector heat loss by convection. Fresnel lens and/or tracking-concentrating collectors increase the incoming solar energy per unit area, whereas heat loss increases only slightly (due to higher Δt). Both of these approaches are expensive, and tracking collectors require added maintenance for the tracking mechanism. Selective surfaces represent a simple, relatively cheap improvement over flat black collectors (compare *D* to *B*); they absorb solar energy just as well but emit radiant energy at a vastly lower rate, thus cutting collector heat loss by radiation.

STEP 3. *Approximate system efficiency.* Once the hot water leaves a collector, it must be led back to storage. In indirect systems, it must go through a heat exchanger. The tank will lose some heat; heat losses also occur as the cooled water is led back to the collector. Another "loss" to be considered is noncollection time. Estimates of collector performance are based on total daily insolation, yet the first few and last few hours of daylight generally will *not* bring enough insolation to warm the collector. Therefore, some reduction should be made in daily insolation totals when performance is estimated. All these factors can be accounted for by assuming a lower system efficiency. A perhaps optimistic assumption is that system efficiency = 0.8 × collector efficiency.

STEP 4. *Determine the total heat needed for DHW.* Estimates of the quantity of hot water needed were made in Section 19.6(h). Once the total gallons (or liters) per day are known and the desired storage temperature determined, the heat needed for the daily supply of DHW is easy to calculate. In I-P units:

$$Q = 8.33\ (\text{gpd})\ (t_s - t_g)$$

where

Q = daily heat need, Btu
8.33 = weight of water, pounds per gallon × Btu/lb °F
t_s = storage temperature, °F (see Table 19.7)
t_g = groundwater temperature, °F (see Fig. 10.31, well-water temperatures)

In SI units:

$$Q = 1.16\ (\text{L/d})\ (t_s - t_g)$$

where

Q = daily heat need, Wh
1.16 = the SI equivalent of the 8.33 factor
t_s = storage temperature, °C
t_g = groundwater temperature, °C

STEP 5. *Determine the desired percentage solar contribution to DHW.* There are several approaches to this problem. One common strategy is to have solar provide 100% of hot water needs in the best insolation month. A closely related strategy is to choose the *yearly* percentage of solar heat desired and then provide that percentage in the average month (such as March). Whatever strategy is chosen, a month and its percentage of solar heat must be identified.

STEP 6. *Size the collector.* This is done by combining the aforementioned steps as follows:

Collector area

$$= \frac{\text{daily heat need} \times \text{percent solar desired}}{\text{daily insolation} \times \text{system efficiency}}$$

This may be done for several months as a check on optimum collector size.

EXAMPLE 19.4 Determine the approximate size of solar collectors needed to serve the women's dormitory described in Example 19.3. Assume the location to be Springfield, Illinois.

STEP 1. *Tilt angle.* Refer to Appendix C (Table C.19 [C.20 for SI]). Springfield's latitude is 39.8°N. In Table C.19 (C.20), average insolation is given for July. Use this month as the best month.

From Table C.12 (C.16 for SI), the optimum tilt angle for July at 40°N latitude is horizontal. However, at 30° tilt (latitude minus 10°), much better performance will be obtained in average months, such as March and September. Choose a 30° tilt angle.

STEP 2. *Collector efficiency.* For the best month (July), the best hourly clear-day insolation is 307 Btu/h per ft^2 (969 W/m^2), at 30° tilt, in the hour centered at noon. To adjust this for *average* hourly value, calculate

$$307 \times \frac{2058\ \text{Btu/day average horizontal*}}{2534\ \text{Btu/day clear horizontal**}}$$
$$= 249\ \text{Btu/h per ft}^2$$
$$(969 \times 2171\ \text{kJ}/2673\ \text{kJ} = 787\ \text{W/m}^2)$$

*Table C.19 (C.20 for SI); **Table C.12 (C.16 for SI)

Outdoor average temperature (TA) is approximately obtainable from Table C.19 (C.20 for SI); TA for July is 76°F (24.4°C). This is quite conservative, since it is the average daily temperature; the temperature at noon should be higher. From Appendix B, the mean daily range for Springfield is 19.2F° (10.7C°). Thus, 76 + 19.2/2 = about 86°F [24.4 + (10.7/2) = 29.8°C]. The thermostat setpoint temperature of the water storage tank is assumed to be 115°F (46°C). This allows adequately hot water for most dormitory uses, although a higher temperature will be required for the cafeteria's dishwashing.

Assume, because it is summer, that T_i is at the set-point of 115°F (46°C). (In winter, it would be lower.) Therefore, the quantity $(T_i - T_a)/I_o$ can be calculated at

$$\frac{115°F - 86°F}{249 \text{ Btu/h ft}^2} = 0.116$$

[in SI (46°C – 29.8°C) / 787 W/m^2 = 0.021]

Enter Fig. 19.36 with this number, and assume a single-glazed, flat-plate selective surface collector (type D). The efficiency will be about 70% under these conditions.

STEP 3. *System efficiency.* Use the design guideline

0.8 (70% collector efficiency) = 56%

STEP 4. *Total heat needed.* The average usage in gpd (L/d) can be estimated from Table 19.21. For women's dormitories, the rate is 12.3 gal/student × 300 students = 3690 gal (46.6 L/student × 300 = 13,980 L). For the cafeteria, the average rate (type A) is 2.4 gal/meal = 2.4 × 300 = 720 gal (9.1 L/meal × 300 = 2730 L). Total volume needed: 3690 + 720 = 4410 gal (13,980 + 2730 = 16,710 L).

Groundwater temperature for Springfield (from Fig. 10.31) is about 56°F (13.3°C). Assume that solar energy will be used to raise it to 115°F (46°C).

Q = 8.33 (4410 gpd) (115 – 56) = 2,167,380 Btu

[Q = 1.16 (16,710 L/d) (46 – 13.3) = 634 kWh]

STEP 5. *Desired percent solar.* For this best hour in July, assume a 100% solar contribution.

STEP 6. *Collector size.* Average daily insolation can be obtained from Appendix C as before:

Clear day total, 30° tilt, July: 2409 Btu (0.706 kWh) (Table C.12 [C.16 for SI])

Clear day total, horizontal, July: 2534 Btu (0.743 kWh) (Table C.12 [C.16 for SI])

Average day total, horizontal, July: 2058 Btu (0.603 kWh) (Table C.19 [C.20 for SI])

Average July daily insolation (per ft^2), at 30° tilt = 2409 × 2058/2534 = 1956 Btu/ft^2 day

(0.706 × 0.603/0.743 = 0.573 kWh/ft^2
= 6.17 kWh/m^2)

$$\text{collector area} = \frac{(\text{load} \times \text{solar contribution})}{(\text{insolation} \times \text{system efficiency})}$$
$$= \frac{2{,}167{,}380 \text{ Btu} \times 100\%}{1956 \text{ Btu/ft}^2 \times 56\%}$$
$$= 1979 \text{ ft}^2$$

[(634 kWh × 100%)/(6.17 kWh/m^2 × 56%) = 184 m^2]

This size should be checked against the average-month performance and adjusted as desired. Note that this is a ratio of about 1979/300 = 6.6 ft^2 (184/300 = 0.6 m^2) of collector per student—lower than the general rule for typical residential DHW systems.

Note also that at the design guideline rate of 1 to 1.5 gal (3.8 to 5.7 L) of storage per square foot of collector, a tank size of 2000 to 3000 gal (7570 to 11,355 L) is indicated. In Example 19.3, the minimum recovery rate required a storage tank of 8150 gal (≈30,670 L), and the fastest recovery rate required 3010 gal (≈11,370 L). Either seems sufficient for this size of collector array. ■

Swimming pool heating is an especially attractive application for solar energy. A common design guideline for collector sizing is

Collector area = 0.5 pool surface area

For summer ambient temperature operations, unglazed collectors are both the best-performing and the least expensive, as explained for Fig. 19.36. Another important consideration is a pool cover, which will not only conserve the pool's heat but also reduce water lost by evaporation. On very hot and dry days, water losses can reach 100 gpd from a 20-ft × 40-ft pool (380 L/day from a 6-m × 12-m pool).

(j) Heat Pump Water Heaters

Air-water heat pumps are also used for DHW, as shown in Fig. 19.37. Because these devices remove heat from the air, they are usually installed either in normally overheated spaces (such as restaurant kitchens) or in unheated spaces such as garages or basements. (They can also remove heat from exhaust air, as explained in Chapter 5.) The spaces that contain these units will be cooled and dehumidified. Heat pumps require only a little more space than the simple hot-water storage tanks they serve. Some noise is created by the compressor and the fan that moves air across the evaporator.

Heat rejected from any refrigeration unit can be used for heating water via the heat pump. Applications include ice-making machines, refrigerated display units in grocery stores, walk-in freezers, and many others. Whenever constant refrigeration loads are present, there is an opportunity to utilize waste heat.

Graywater provides another opportunity for using a heat pump. Where filtered graywater is

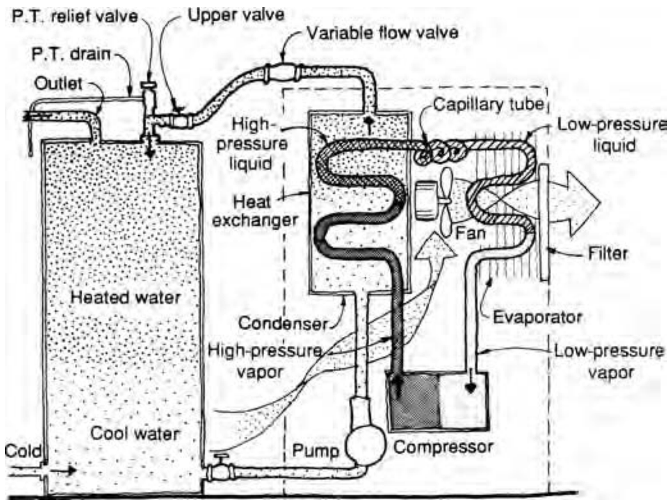


Fig. 19.37 *Heat pump (air–water) used for heating DHW. (Adapted by permission from* Specifying Engineer*, October 1983. © 1983 by Cahners Publishing Co.)*

collected for recycling on site (as for irrigation systems), a water–water heat pump can heat a DHW storage tank as it lowers the graywater tank temperature. See Chapter 20 for graywater system design.

19.7 FIXTURES AND WATER CONSERVATION

Building design and fixture choice can affect water and energy consumption over the life of a building. It is the users who turn the faucets on and off, but the designer who can encourage resource conservation through initial decisions, here centered largely in kitchens and bathrooms.

Visible consumption is one strategy to encourage the users of fixtures to conserve water. We see, hear, feel, and sometimes taste water as it issues from a fixture. If we could see *how much* water is involved in each use, we could more readily alter our pattern of use to conserve water where appropriate. Rainwater storage tanks outside bathroom windows, used to flush toilets, might have a visible indicator of the water level; the lower this level, the more that conservation is an imperative. The water-level indicator might be as simple as visible condensation on the tank's outer surface. Strategies as simple as supplying water to lavatory sinks through small, transparent tanks of clean supply water placed above, might encourage occupants to use only a portion of the water already in the tank. Sufficient pressure at the fixture is achieved by such a tank's elevation above the fixture. The designer might also consider making the quantity of used (waste) water visible, but such water is often unsightly and the resulting quantity is "after the fact"—too late to conserve.

Audible consumption is another strategy, calling attention to the flow of supply (or waste) water. This is achieved most simply by slightly undersizing water supply pipes so that the water velocity becomes audible (at about 10 fps [3 m/s]). This strategy should be carefully considered; it is one thing to inform the water user, another to annoy. Audible flow is perhaps best justified on lines to exterior hose bibbs, where irrigation or car-washing hoses may inadvertently be left on.

Elimination of bodily wastes accounts for a significant portion of residential water usage (see Chapter 20), and bathing accounts for a significant portion of residential hot water usage (see Table 19.7). The choice of fixtures can have an impact on water conservation, and on energy conservation where hot water is involved. The bathroom is thus a site for potential resource conservation.

(a) Physiology, Psychology, and Fixtures

One of the more challenging aspects of bathroom design is the frequent conflict between physiological design criteria and such psychological influences as cultural attitudes about bathroom activities. Physiological criteria change as slowly as evolution. Cultural attitudes can change very rapidly, even within a generation. The bathroom supports two primary human activities: cleansing and elimination. Today's common attitudes about these closely linked activities are that one is "clean," the other "dirty." One might be discussed (although rarely) among friends; the other is simply not fit for conversation. This conflict in attitudes influences the design of our plumbing fixtures. The toilet is the fixture used for elimination; it is the logical place to provide for the cleansing of the perineal zone that should immediately follow elimination. (This is especially true of public toilets, where stalls close off toilets from lavatories.) Yet very few toilets presently incorporate a cleansing feature: the mixture of cleansing and elimination in the same fixture too often seems abhorrent.

The brief summary presented in this section is based largely on a particularly revealing (and entertaining) study of the struggle between physiological and cultural criteria in fixture and bathroom design—Alexander Kira's *The Bathroom: Criteria for Design*, an expanded edition of which was published in 1976 by Viking Press.

Fig. 19.38 *Proposed lavatory that exploits running water. The water issues in a fountain-like stream for ease in drinking and in hair and face washing. The stream strikes the lavatory bowl in such a way as to minimize splashing outside the bowl, yet sets up a self-cleaning swirling action. A small repository at the back of the bowl, over the drain, can serve for standing water when desired. (From* The Bathroom, *new and expanded edition; © 1966, 1976 by Alexander Kira. By permission of Bantam Books, a division of Random House, Inc. All rights reserved.)*

(b) Lavatories

A key issue here is the contrast between running water and a standing water body. Lavatories are used primarily for the cleansing of hands, face, and teeth—activities done quickly with running water that is wasted directly rather than being collected. Most lavatories are designed as collection bowls—perhaps a reflection of the days when washbasins of standing water, drawn and heated elsewhere, were brought to the bathing place. Most lavatories also have fittings that project out over the sink. Although these fittings have slowly evolved into very sleekly designed objects, most of them still dump running water directly into the drain, are hard to use as drinking fountains, and can wound those who try to wash their hair in the lavatory. In considering the prevalence of running as opposed to standing water, the role that running water could play in keeping lavatory surfaces clean, and the need for a drinking fountain when teeth are brushed, Kira proposed a quite different lavatory design (Fig. 19.38).

At full flow, lavatory faucets typically deliver 4 to 5 gpm (0.25 to 0.3 L/s). Newer low-flow faucets utilize a variety of devices to function as well (or better) with less water. Such devices include aerators (which add air bubbles to the stream, making it splash less and appear larger), flow restrictors, and mixing valves to control temperature. The lower flows achieved range from ½ to 2½ gpm (0.03 to 0.16 L/s). Another promising development is the foot-operated faucet, which frees the hands from having to control water flow, thus saving a few seconds of flow during each lavatory usage. These devices could be particularly helpful at kitchen sinks, where extensive washing of objects takes place.

(c) Whole-Body Cleansing

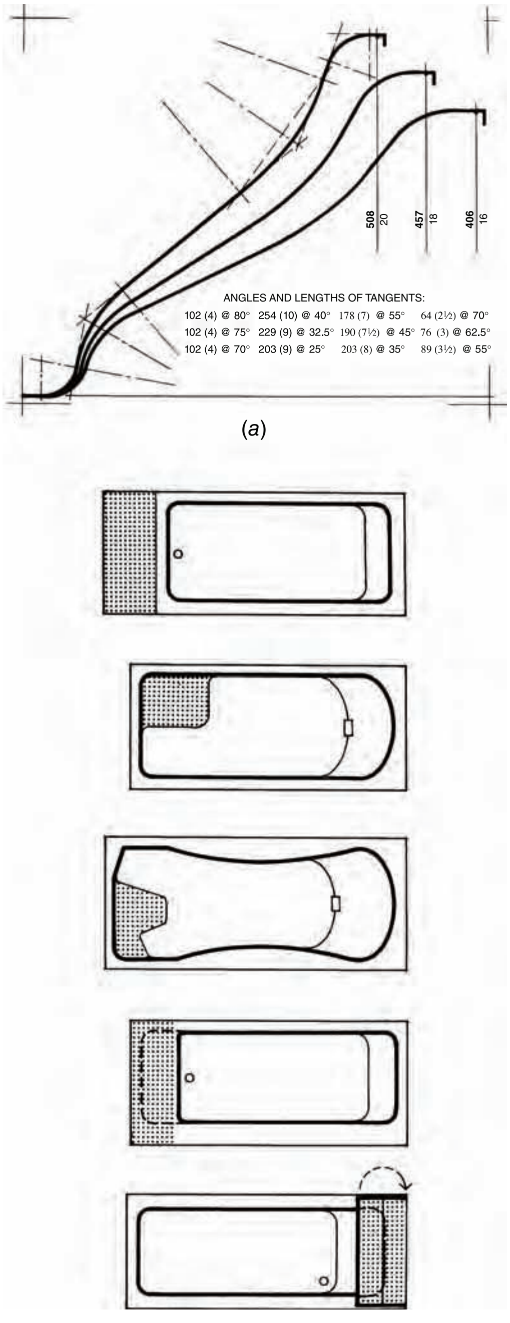
The running/standing water contrast is even more clearly illustrated here. In cleansing, the ordinary sequence is *wet, soap, scrub, and rinse*. Standing water is good for wetting and very good for soaping/scrubbing; running water is superior for rinsing. The psychological aspect enters here in common attitudes toward tubs and showers. Tubs are often seen as places to relax in, to spend more time in, and perhaps to read in. Showers are viewed as quicker, "no-nonsense," stand-up places. Yet each could benefit from some features of the other.

Tubs should be designed so that the reclining body is supported at the back; this requires a contoured surface (Fig. 19.39) rather than the ordinary straight-line design. It also requires braces for one's feet because otherwise the body will tend to float up and away from such a backrest. Tubs can be designed to accommodate persons of various leg lengths, as shown in Fig. 19.39*b*. There must also be a seat to give most of the body a chance to be out of the water and to facilitate safe entry into and exit from the tub. Especially needed is a handheld shower for the final rinse; soapy standing water leaves a scummy film on both people and fixtures.

Showers may seem very efficient, but cleaning would be more thorough and safe if the bather could turn off the water and sit for at least part of the soap/scrub activity, especially for the lower legs and feet. Showers with integral seats are now common.

Another consideration is the location of water controls (fittings). The user should be able to reach them easily from outside the tub or shower without wetting his or her arm, but also should be able to manipulate them from within the tub/shower even if temporarily blinded by soap.

Shower heads have been notorious for encouraging prodigal water usage; typical flow rates of 6 gpm (0.4 L/s) and maximum rates of 12 gpm (0.7 L/s) once were common. Even in a short (5-minute) shower, this rate of use could consume as much as 60 gal (227 L) of water, much of it heated. Many codes now require a limitation on showerhead flow; a flow of 2.5 gpm (0.2 L/s) is common. These flows can be designed into the shower head, or they can be achieved by cheap, simple flow restrictors in retrofit applications. Some utilities distribute flow restrictors free of charge. Most bathers notice no difference, either in enjoyment or in cleansing, when using restricted-flow shower heads.

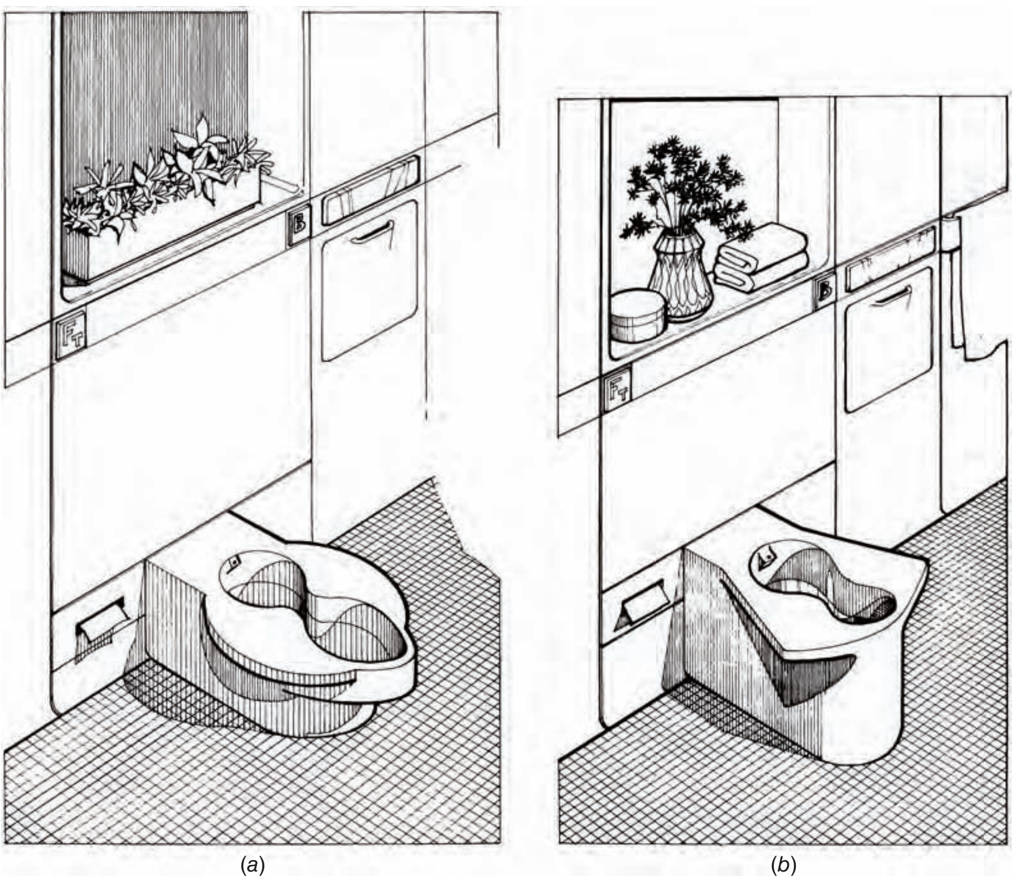


(*b*)

Fig. 19.39 *Some considerations for tub design to facilitate relaxation during whole-body cleansing. (a) A contoured backrest allows comfortable reclining, with support of both the shoulder and lower back. Curve 2, with a median angle of 32.5°, promises comfort for most users. (b) Various tub plans, allowing long- and short-legged persons to brace their bodies against the contoured backrest. Raised seats are also provided to facilitate safe entry/exit. (From* The Bathroom, *new and expanded edition; © 1966, 1976 by Alexander Kira. By permission of Bantam Books, a division of Random House, Inc. All rights reserved.)*

(d) Elimination

Several conflicts arise with toilets: the already-mentioned difficulty of combining cleansing with elimination, the issue of pure (high-grade) water for an impure (low-grade) purpose, and the conflict over the height of the toilet. A *lower toilet* is definitely of benefit to the average person, who will achieve far better bowel evacuation in a full squatting position. If combined with a toilet seat contoured to best support the body during defecation, the proposed toilet in Fig. 19.40*a* would be physiologically superior to most of today's fixtures. There are problems with low height. The typical male stands while urinating, and a lower toilet presents a more difficult target. This can have serious maintenance consequences unless males can be induced to sit, or a separate urinal is provided—an unlikely option for residential bathrooms. (In our culture, urinals look institutional; they are also expensive.) Another problem with a lower toilet is that the elderly and some handicapped people will have difficulty getting on and off the seat (see Fig. 19.51). Yet another problem arises from the fact that toilets are considered to be seats (for reading, toenail clipping, etc.). The low, squat-inducing toilet is decidedly not at a comfortable chair height.



(*a*) (*b*)

Fig. 19.40 *Two approaches to water closets (toilets) that encourage better posture during defecation and more thorough perineal cleansing. (a) A low toilet allows the best (full-squat) position. (b) The higher toilet is easier for the elderly and handicapped and better intercepts the urine from a standing male. Both of these toilets eliminate the separate toilet seat and its maintenance problems; both use small amounts of energy to warm the toilet at its point of contact with the body and to heat the water for perineal cleansing. Such cleansing is also the reason for the larger front and back openings. The pushbuttons are labeled* F_T *for the flush and B for the bidet (cleansing) function. (From* The Bathroom, *new and expanded edition; © 1966, 1976 by Alexander Kira. By permission of Bantam Books, a division of Random House, Inc. All rights reserved.)*

As a result, a *higher toilet* with otherwise similar features is proposed (Fig. 19.40*b*). Note that both of these toilets feature openings whose shape differs from that of the conventional oval. This hourglass-shaped opening provides proper support for the body during defecation, and it allows a more generous opening, front and back, for proper perineal cleansing by hand. Another change is that there is no separate toilet seat; instead, these fixtures incorporate electric resistance heaters that warm the small portion of the toilet that contacts the body. Thus, the toilet becomes a consumer of energy—which is also used to heat the water that is provided for perineal cleansing. For those who insist on a separate seat, or for ordinary posture on conventional toilets, a physiologically sound contoured toilet seat is available (Fig. 19.41).

It is especially important that perineal cleansing be encouraged by the designers of bathrooms. The typical dry toilet tissue provided usually is not adequate for this task. In small, private bathrooms this problem is easily solved by placement of the toilet adjacent to the lavatory (or tub), where toilet tissue can be wetted with clean water. In public toilets separated by stalls, perineal cleansing requires either a clean water source built into the toilet or a separate *bidet* within the stall—a highly unlikely provision, given the extra floor space and the cost of the bidet. Again, cultural issues arise: bidets are quite common in the private bathrooms of Europe but a rarity in North America. Two common alternatives are (1) to build a cleansing source into the toilet itself (Fig. 19.42) or (2) to construct a toilet seat that provides for such cleansing. Several American manufacturers offer such seats, which can be easily adapted to existing toilets. Using recycled water in a toilet that also offers perineal cleansing complicates the high-grade water issue. Codes often require recycled water to be colored (blue or green), an aesthetic quality unappealing for skin contact even in one's nether regions.

The *urinal* is an answer to the problem posed by lower toilets to males, who stand while urinating.

Fig. 19.41 *Toilet seat for a conventional water closet, which encourages better posture for defecation and somewhat better access for perineal cleansing. (Courtesy of American Standard, Inc.)*

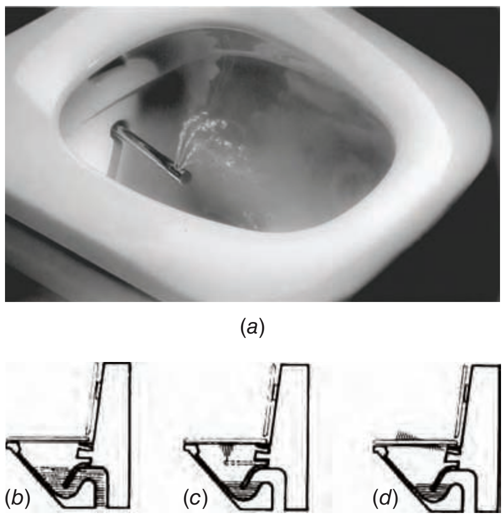


Fig. 19.42 *Provisions for perineal cleansing built into toilets. (a) An adjustable-intensity spray at warm (body) temperature continues for as long as a button is depressed in this Geberit ShowerToilet. (Courtesy of Geberit Manufacturing Inc., Michigan City, IN.) (b) Section through the toilet before/after the cleansing function. (c) At the initiation of perineal cleansing, a pipe extends and emits a controlled spray of warm water. (d) After the pipe is retracted, a warm jet of air issues from just below the seat. (From* The Bathroom, *new and expanded edition; © 1966, 1976 by Alexander Kira. By permission of Bantam Books, a division of Random House, Inc. All rights reserved.)*

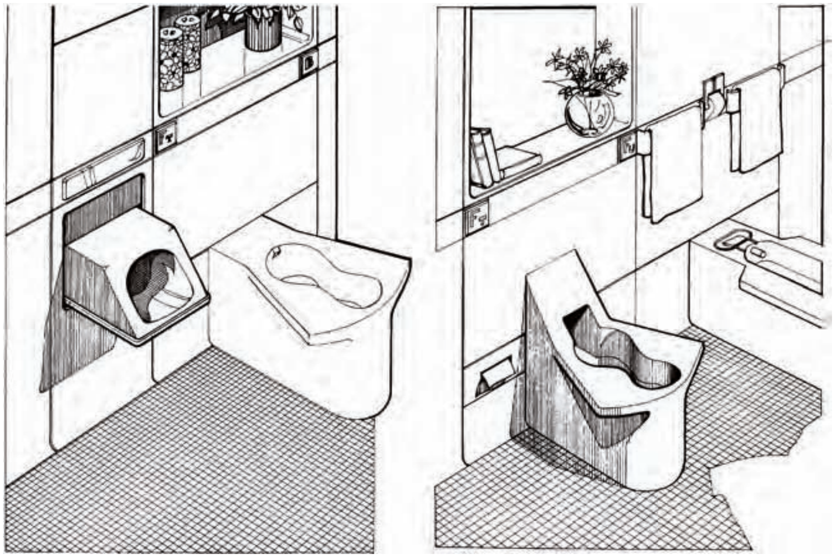


Fig. 19.43 *Designs to accommodate male urination. (a) A built-in, tilt-out urinal for the home, visible only when in use. (b) A higher back for a toilet. A bidet for cleansing is shown to the right of the toilet. (From* The Bathroom*, new and expanded edition; © 1966, 1976 by Alexander Kira. By permission of Bantam Books, a division of Random House, Inc. All rights reserved.)*

Although urinals are culturally acceptable in public toilet rooms, they have never achieved a place in private bathrooms. One solution proposed by Alexander Kira is to build the home urinal into the wall (Fig. 19.43*a*); it could be pulled out for use, at the optimum mounting height, and at an optimum receiving shape to eliminate backsplash onto the user. When pushed back into the wall, it would flush automatically. A less satisfactory solution would be to modify the toilet by raising its back surface (Fig. 19.43*b*).

For the toilet (water closet), there are four major categories of fixtures, depending upon the amount of water used per flush. The *conventional* toilet uses 3.5 gal (13.2 L) or more per flush; the *watersaver* toilet uses 1.7 to 3.5 gal (6.4 to 13.2 L) per flush; the *low-consumption* toilet (also called *ultra-low flush*) uses 1.6 gal (6 L) or less per flush; and the *waterless* toilet uses no water at all.

(e) Conventional Toilets

These toilets may no longer be legally installed in the United States due to their high water consumption. They are still widely encountered in existing installations. In the common toilet, a sudden deluge of water removes human waste and simultaneously helps cleanse the toilet. Fast-moving water requires pressure and makes noise. The older flush-tank toilet (Fig. 19.44*a*) stores a smaller quantity of water (about 2.5 gal [9.5 L]) at sufficient height above the toilet bowl to achieve fast flow. Although it uses minimal amounts of water, it is noisy, and its elevated tank has maximum visual impact. The more common (in North America) version is the two-piece toilet with the tank bolted to the bowl (Fig. 19.44*b*). With much less pressure available, this toilet requires 5 to 7 gal (19 to 26 L) per flush, but it is quieter. Newer *shallow-trap* models reduce the quantity needed to 3.5 gal (13.2 L). The maintenance problem posed by the seam between tank and toilet is eliminated in the one-piece toilet (Fig. 19.44*c*). The cost of its low profile is an even greater need for water: 6 to 8 gal (23 to 30 L) per flush.

The fourth common alternative is the flush-valve toilet, which depends upon the building's water pressure rather than its own stored water. A noisy system requiring very high flow rates, it is seldom found in residences. However, it requires as little as 3 gal (11.4 L) per flush.

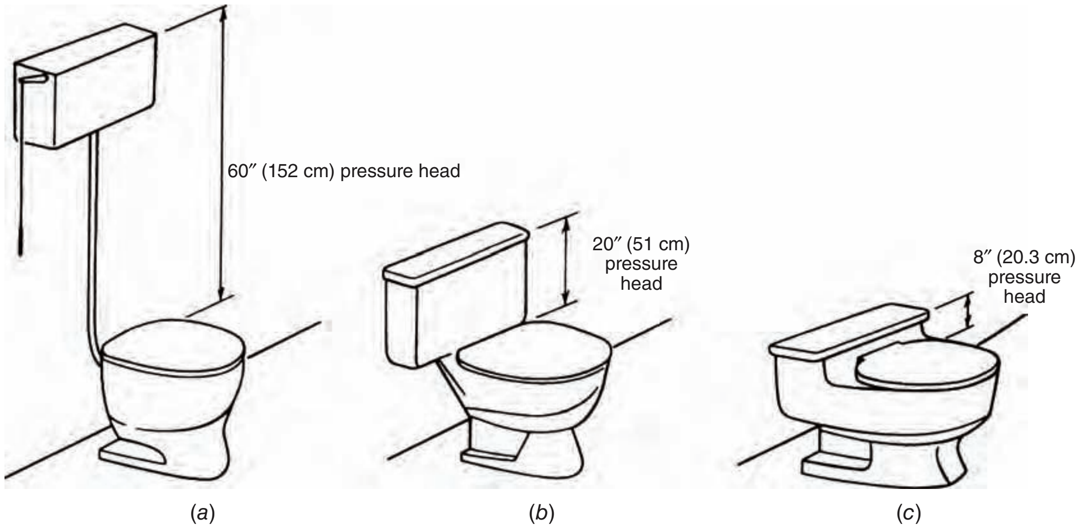


Fig. 19.44 *Conventional flush tank toilets. (a) Two-piece flush tank toilet with an elevated wall-mounted tank and pull chain. (b) Two-piece flush tank toilet with the tank bolted to the bowl ("close-coupled"). (c) One-piece flush tank toilet with an integral tank. (From Milne, 1976.)*

In addition to differing tank and bowl combinations, there are various types of flushing actions. Four common flush toilets are compared in Fig. 19.45.

Washdown toilets are no longer made in the United States, although many are still in use. This is the noisiest toilet and the most likely to become plugged because it has the smallest-diameter trap. It is usually found in the two-piece flush tank toilet; with an elevated tank, the flush required was only about 2.5 gal (9.5 L).

Siphon jet toilets are in widespread use in North America, particularly in residences. A small priming jet hurries the bowl's contents into the trap and hastens the siphon action. With an elevated-tank (two-piece) toilet, this process requires a flush of about 3.75 gal (14.2 L). With the more common close-coupled two-piece toilet, it requires a flush of 5 to 7 gal (19 to 26.5 L). Siphon jet toilets are sometimes equipped with flush valves, which use less water (see the discussion of blowout toilets that follows).

Siphon vortex toilets are especially suitable for low-velocity water (often as a result of low pressure). They are therefore also the quietest, making them a favorite wherever bathrooms are adjacent to sleeping areas or other acoustically sensitive spaces. The water enters the bowl off-center in such a way as to form a vortex; this swirling action cleans the sides of the bowl and the trap, helping the siphon action in emptying both bowl and trap. The one-piece flush tank toilets usually have the siphon vortex flushing action, which typically requires 6 to 8 gal (23 to 30 L).

Blowout toilets combine very-high-velocity water and a simple trap to offer a noisy but very low-maintenance toilet dependent upon flush valves rather than tanks. They are very common in commercial and institutional toilet rooms, where large water supply lines and high pressures are available. The high velocity of the water lowers the quantity required from 3 to 4 gal (11.4 to 15.1 L) per flush.

Architects can easily specify toilets that require less water per flush and yet have very little impact on the user. With effort on the part of both users and architects, water can be recycled, or rainwater collected, to supply toilets with lower-quality water.

(f) Watersaver Toilets

These use 1.7 to 3.5 gal (6.4 to 13.2 L) per flush. Although these toilets use much less water than conventional ones, they may not meet the stricter water

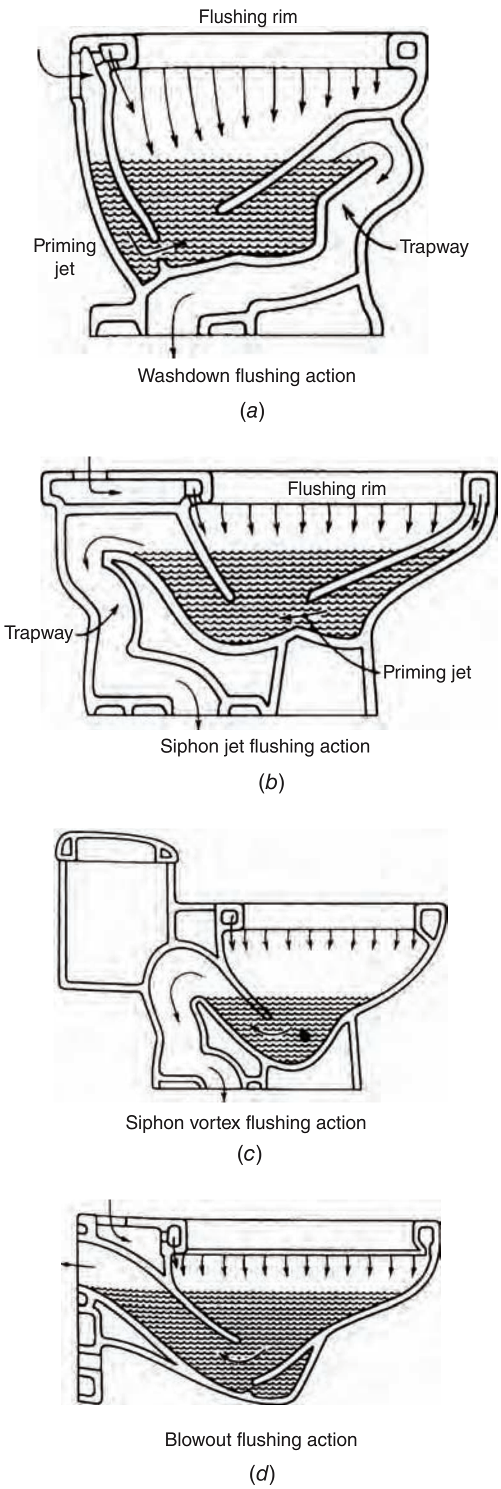


Fig. 19.45 *Four common flushing actions that are built into toilets. Flush tank toilets typically use either type (b) or type (c); flush valve toilets use either type (b) or type (d). (From Milne, 1976.)*

limits now established in many water-conscious states and municipalities in the United States (toilets must not exceed 1.6 gal [6 L] per flush). Many of these toilets represent a compromise between the conventional "water waster" and the noisy operation and/or smaller water surface area that typifies so many low-consumption models. Watersaver toilets tend to use a conventional flushing action, and hence need enough height between the tank and the bowl to provide sufficient water pressure within the bowl during the flush.

Toilets can be designed to use less water by varying several characteristics: the pressure of the water entering the bowl (generated either by the height of the tank above the bowl or by utilizing pressure from the water supply system or another source), the shape of the bowl, the way in which the bowl fills and empties, and the trap configuration. Watersaver toilets differ somewhat in most of these characteristics from a conventional toilet; more radical changes are needed to achieve a low-consumption toilet.

(g) Low-Consumption Toilets

These use 1.6 gal (6 L) or less per flush. A heated controversy over these ultra-low-flush water closets developed in the late 1990s due in part to steep price increases and consumer discontent over performance. It appears that regulation got ahead of technology for a time, resulting in a need for repeated low-consumption flushes to accomplish what one higher-consumption flush could do. To remove fecal matter, however, two 1.6-gal (6-L) flushes still approximately equal the old 3.5-gal (13.2-L) flush; to flush urine, one 1.6-gal (6-L) flush is adequate. Manufacturers are finding ways to change the entry point of water into the toilet bowl to increase swirl and thus waste-removal power.

Several of these toilets achieve water conservation by using a *flushometer tank* (Fig. 19.46). Satisfactory flushing can be achieved with much less water by flushing with water entering at greater pressure. Instead of toilet tanks at ordinary air pressure, these tanks utilize water supply system pressure to compress air trapped within the tank. Water enters the bowl with much greater force with this combination of water under system pressure and compressed air. The flush is thorough, quick, and noisy. If the water supply pressure is greater than about 65 psi (448 kPa),

Fig. 19.46 *Example of a 1.5-gal-flush (5.7-L), pressure-assisted, direct-fed siphon jet flush action flushometer tank, with a large 10 in. × 12 in. (250 mm × 300 mm) water surface area in the bowl: the Cadet Aquameter. (Courtesy of American Standard, Inc., Piscataway, NJ.)*

some problems with excessive tank pressures may be expected. A pressure-reducing valve would be helpful in such cases.

Another water-saving technique is to redesign the bowl to hold less water. The siphon jet, gravity-fed toilet whose tank is shown in Fig. 19.47 exposes a standing water surface of about 4½ × 6 in. (114 × 152 mm), much smaller than that in Fig. 19.46. Along with a very low 1.4-gal (5.3-L) flush, its trap is wide enough to pass a 2⅛-in. (54-mm) ball.

Far lower water consumption is achieved when a central compressed air system is combined with water supply system pressure. The Microphor flush toilet (Fig. 19.48) uses compressed air and 2 qt (1.9 L) of water per flush in a two-chambered toilet. When the flush lever is pressed, the water and waste in the bowl (upper chamber) are deposited into the secondary (lower) chamber, and 2 qt (1.9 L) of water (direct from the supply pipe) wash down the sides of the bowl to await the next user. The now-closed secondary chamber then is pressurized with compressed air, and its contents are deposited into a conventional sewer line.

Air compressors are needed, along with compressed air lines. A small compressor (¼ to ½ hp [187 to 373 W]) with an accompanying air tank will operate up to three toilets. Although the compressor is noisy, the toilets themselves are no noisier than conventional toilets; they use the same plumbing lines. With such low flows, the designer may choose to increase the slope of waste lines; however, the 2-qt (1.9-L) quantity has proven sufficient to carry the waste in existing installations.

In contrast, the Envirovac flush toilet (Fig. 19.49) uses a vacuum and 1.5 qt (1.4 L) per

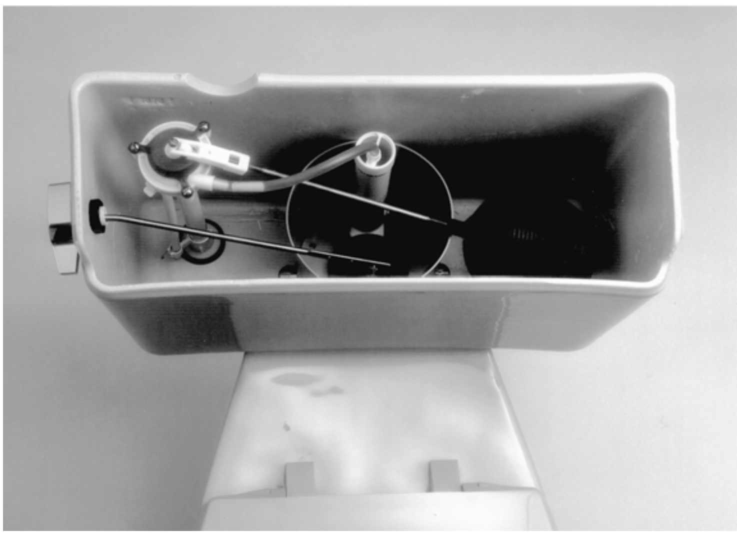


Fig. 19.47 *A very-low-flow flush is achieved with a reservoir that meters about 1.4 gal (5.3 L) of water from the tank to the bowl during flushing. The standing water surface is about 4½ by 6 in. (115 by 150 mm). The Ultra-One/G. (Courtesy of Eljer Industries, Plano, TX.)*

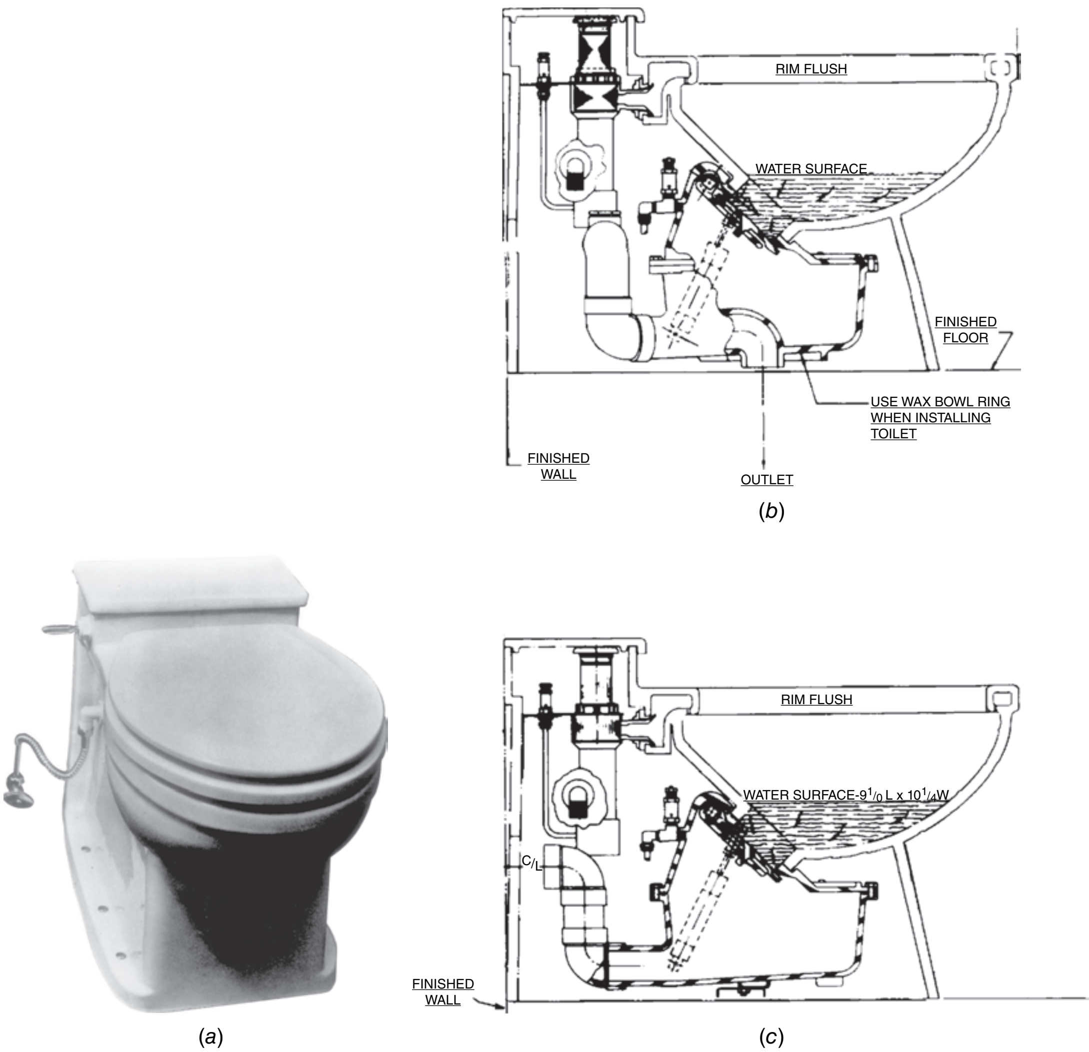


Fig. 19.48 *(a) Compressed air is combined with a 2-qt (1.9-L) flush in the two-chamber Microphor toilet. (b) Section through the floor-discharge model. (c) Section through the wall-discharge model. (Courtesy of the Microphor Company, Willits, CA.)*

flush. Because a central sewage tank (kept under vacuum by a pump) must be used, the drain line from the toilet to this tank may run horizontally without a slope or may even run vertically upward from the toilet. This can have significant architectural advantages when vertical clearance is tight, toilets are being added within existing structures, or toilets must be located below the level of the public sewer, as in marinas or basements. In tall buildings, significant savings in power for water supply pumping are achieved. Easier approval for building permits, reduced water hook-up fees, and lower monthly sewer charges can be substantial benefits. Furthermore, the central sewage holding tank can be flushed into the sewer at off-peak times—a benefit to the treatment plant. These water-saving, architectural, and water treatment advantages must be weighed against the cost of the toilets and the tank/pump combinations, the space required for the tank/pump, the power used by the pump, and the possibility that a power failure will halt system operation.

Vacuum systems can be installed for groups of buildings, such as subdivisions. Small pipe sizes, freedom from the need for continuous-sloping sewer lines, and conservation advantages for both water supply and treatment are the benefits. In

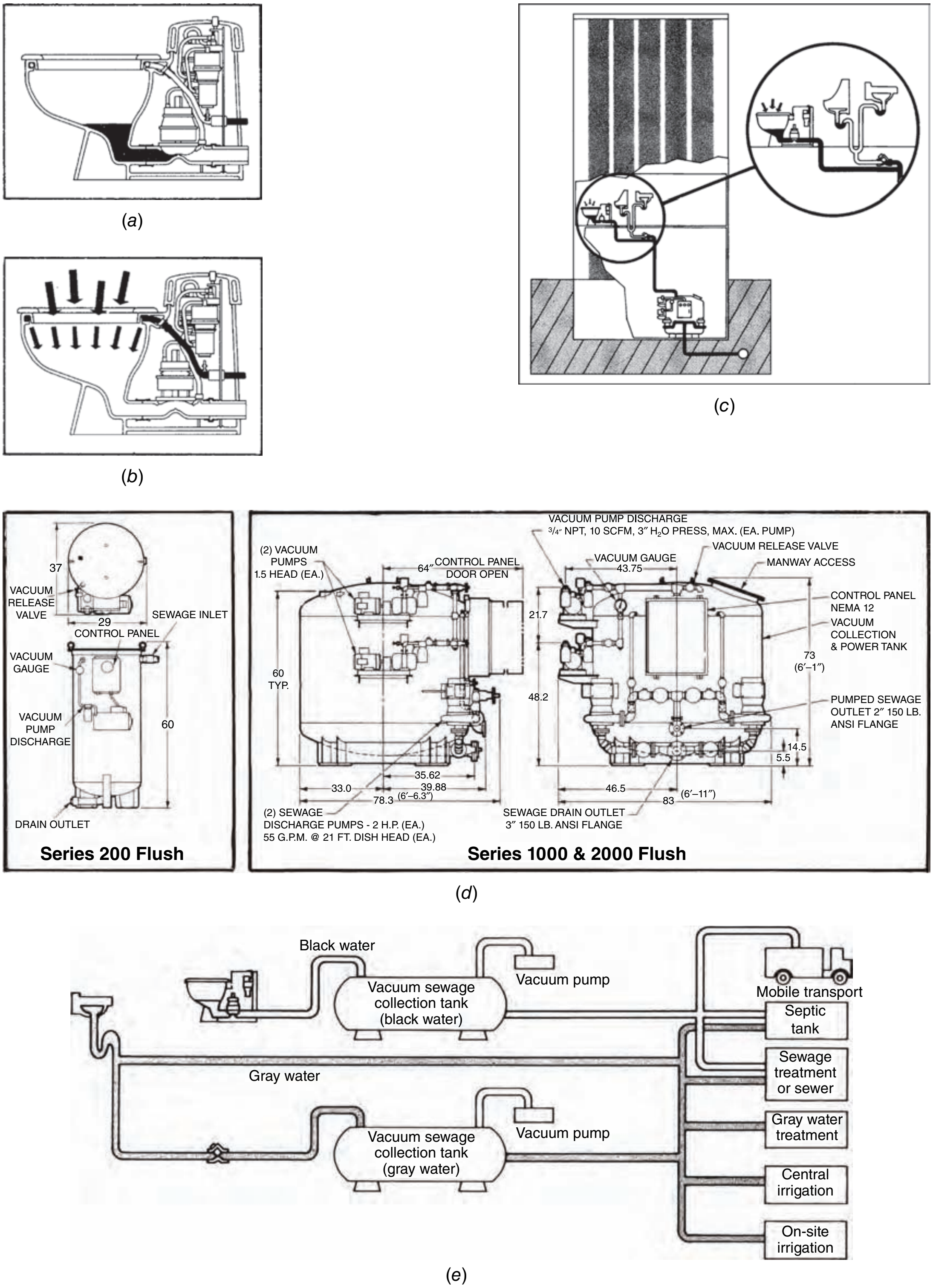


Fig. 19.49 *The Envirovac system utilizes a vacuum and a 3-pt (1.4-L) flush. (a) Less than 3 pints (1.4 L) of water remain in the bowl until the toilet is used. (b) When the pushbutton flush is pressed, the discharge valve opens for about 3 seconds; a rush of air into the evacuated piping carries along sewage, odor, and airborne bacteria. Simultaneously, the washdown water flow begins. The flow continues for 4 seconds after the discharge valve closes, so that most of the 3-pt (1.4-L) flush remains in the bowl. (c) Toilets are directly connected to a central holding tank, kept under a vacuum by a pump. (d) Central tank/pump combinations can serve one house or a large building. (e) The separation of graywater and blackwater is another water-conserving opportunity. (Courtesy of Envirovac, Inc., Rockford, IL.)*

addition, graywater (from kitchen, laundry, and bathing fixtures) can be kept separate from toilet water (blackwater) and thus made easier to recycle after moderate treatment.

(h) Flushing Controls

Water conservation is encouraged by the *dual-cycle* toilet, whose flushing mechanism allows a choice of fewer gallons for liquid wastes, more gallons for solid wastes. This simple mechanism, though beginning to spread in popularity here, is still more commonly seen outside the United States. Its handle is pushed up for liquid flushing and down for solids.

Another development is the *automatic flush*, common in public buildings and triggered by radiant heat from the pressure of a body at the fixture or by light reflected off the user and back to the control. This "touchless" approach seems to promise more for hygiene than for water conservation, although it does prevent the flush valve from being held open too long by a careless user.

In general, plumbing fixtures will consume less water as the supply water pressure is reduced. For this reason, *pressure-reducing valves* are becoming popular as water conservation devices (when they would not otherwise be required to protect fixtures from overpressure). Installed on the supply line to a building, they can save water throughout the system.

Several newer low-consumption toilets use vertical flush valve sleeves, where the flush handle is in the center of the top of the toilet tank. The handle is lifted to initiate the flush. An advantage is that the less time the handle is raised, the less water enters the bowl. Again, less water may be admitted to flush away liquid waste, more water for solid waste.

(i) Waterless Toilets

Because these fixtures eliminate water entirely, they are described in Chapter 20, Section 20.1.

(j) Appliances

Dishwashers, washing machines, and other appliances are big users of water—and of energy to heat it. Dishwashers use 12 to 18 gal (45 to 68 L) per cycle, much of it heated well beyond the 120°F (48°C) typical of a household hot water supply. Some models now allow shorter cycles, which can cut use to perhaps 7 gal (26.5 L).

Clothes washing machines use 40 to 55 gal (151 to 208 L) for full-sized loads. In the past, "suds saver" features allowed soapy, hot wash water to be reused. Many newer washers allow for a wider selection of water quantities and temperatures—a feature that can save considerable water and energy. Horizontal-axis (front-loading) washers have greatly reduced the need for hot water per wash cycle.

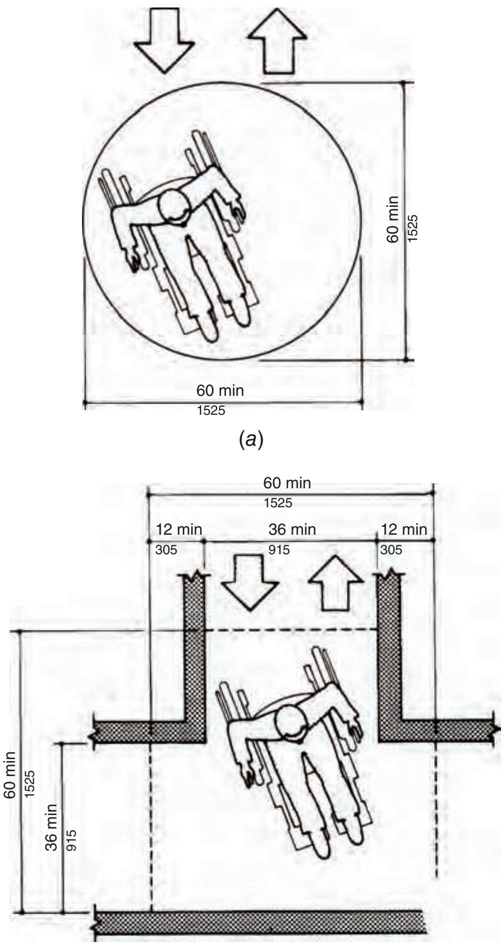
19.8 FIXTURE ACCESSIBILITY AND PRIVACY

After plumbing fixtures designed for the human physique and for water conservation have been chosen, they are placed in a space that has several unusual environmental needs. Much of the information in this section is reproduced with permission from American National Standard for Buildings and Facilities A117.1-1986, *Providing Accessibility and Usability for Physically Handicapped People*, copyright 1986 by the American National Standards Institute (ANSI). Copies of this standard (updated as *Accessible and Usable Buildings and Facilities* in 2003) may be purchased from ANSI, 25 West 43rd Street, New York, NY 10036. Another useful guide is the *Americans with Disabilities Act* (*ADA*) *Accessibility Guidelines for Buildings and Facilities*, available from the U.S. Architectural and Transportation Barriers Compliance Board, Washington, DC.

(a) Accessibility

Designers must allow room for wheelchair maneuvering into and within toilet rooms. The minimum clear floor area should be a circle 5 ft (1.525 m) in diameter. Minimum clearances for wheelchair maneuvering are shown in Fig. 19.50. Provisions for people in wheelchairs also influence the heights at which items such as light switches, electrical receptacles, paper towels, and water controls should be installed. In general, all objects to be reached by hand in toilet rooms should be placed more than 15 in. (380 mm) and less than 48 in. (1.22 m) above the floor.

Floor space requirements and mounting-height limitations also apply to the various



(b)

Fig. 19.50 Wheelchair turning space, minimum requirements. (a) A 60-in. (1.525-m)-diameter space. (b) T-shaped for 180° turns. Dashed lines indicate the minimum length of clear space required on each arm of the T-shaped space. Reprinted by permission from National Standard A117.1-1986; © 1986 by the American National Standards Institute. The dimensions are current as of 2013.

plumbing fixtures in bathrooms, at least one of which (in each case) should be accessible to people in wheelchairs in most buildings. Requirements for drinking fountains (which often must be located outside toilet rooms), lavatories, bathtubs, and shower stalls include clearances beside the fixture (and clearance below lavatories) and grab bar locations; see the ANSI Standard for details.

Accessible toilets (water closets) have particularly large floor space requirements, as shown in Fig. 19.51. There is a conflict between the lower mounting height needed for proper defecation, the conventional height of 15 in. (380 mm), and the recommended height for handicapped users of 17 to 19 in. (430 to 485 mm). The doors on stalls designated for wheelchair access should swing out rather than in. Provision for a wheelchair sitting beside the out-swinging door must also be made. No doors should swing into the clearance space required for any fixture.

Where six or more water closets (or water closets plus urinals) are located within the same toilet room, *both* the "standard stall" and one of the "alternate stalls" are required. This impacts the design of public toilet rooms.

Urinals for handicapped users should either be of the floor-mounted stall type or, if wall-hung, have an elongated rim at a maximum of 17 in. (430 mm) above the floor. A clear floor space of 30 × 48 in. (760 × 1220 mm) is required in front of the urinal, and its flush controls should be no more than 44 in. (1.12 m) above the floor.

(b) Privacy

A desire for visual privacy is easily understood and at least minimally provided by partial-height partitions. However, *acoustic* considerations are another important aspect of bathroom design. Because of their nonabsorbent surfaces, bathrooms are frequently the most reverberant spaces in a building. They encourage the singer or the whistler and may even serve as practice rooms for the family musician. Yet they can also intimidate a person who prefers to be quiet, such as a guest using the toilet while the rest of the dinner party sits quietly in the adjacent room.

Two common design responses are isolation and masking sound. Bathrooms can be separated from acoustically sensitive spaces by closets or hallways. With careful attention to sufficiently massive construction and/or other construction details, the doors, walls, ceilings, and floors of bathrooms can be constructed so as to reduce the passage of sound to acceptably low levels. (These considerations are discussed in Chapters 23 and 24.) Sound isolation also depends upon attention to detail: no cracks around the bathroom door, no back-to-back electrical outlets between bathrooms and adjacent spaces, no air grilles into ducts that have other grilles nearby, and no other open windows near a bathroom window. If such goals are

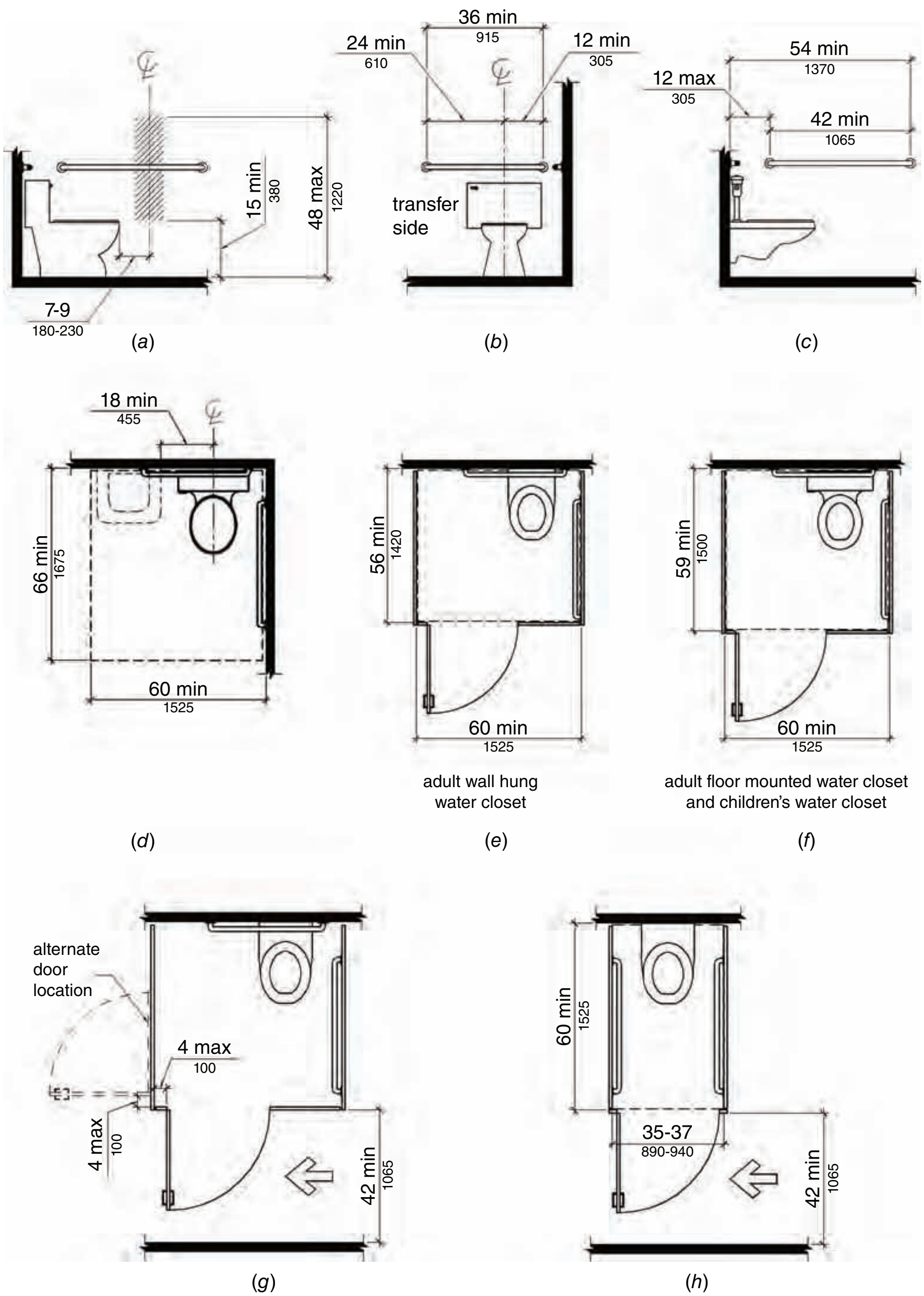


Fig. 19.51 *Clearances and grab bars for toilets. (Reprinted from 2010 ADA Standards, Department of Justice.)*

unattainable or if additional acoustic security is desired, masking sound can be added as needed within the bathroom. All too often, the masking noise is provided by repeated flushings of the toilet (itself an embarrassing sound for some) or the running of water in the lavatory. However, a noisy ventilating fan would serve the purpose, as would a music source such as a radio. An elegant, expensive touch would be a recirculating fountain gracing one corner; it might provide splashing sounds only when the light or fan is on.

The final consideration in bathroom acoustics is the sound of water moving within pipes. Where such pipes are exposed or barely concealed within, or firmly attached to, thin walls, perceptible sounds are highly likely. Where water noise is undesirable, pipes should be wrapped, resiliently mounted, and/or located in a less acoustically critical wall. But remember that running water can also be a conservation signal as well as a masking sound. Although many of us may have experienced this sudden acoustic signal that a bathroom is in use, few have experienced it quite like the occupants of the Aluminaire house on Long Island, cited by Reyner Banham (1969). Designed at the height of the modernist expression of mechanical services, this house featured a dining table cantilevered from the exposed waste stack serving the bathroom above.

19.9 WATER DISTRIBUTION

This section looks at ways to supply water throughout buildings at pressures sufficient to operate plumbing fixtures. Smaller buildings may be served simply by the pressure available in water mains (or pressure tanks fed by pumped wells). This is called *upfeed distribution*, because the water rises directly from mains to the plumbing fixtures. For taller buildings, several other options are available: *pumped upfeed* (in which pumps supply the additional pressure needed), *hydropneumatic* (in which pumps force water into sealed tanks, compressing the air within; this maintains the needed water pressure), and *downfeed* (in which pumps raise the water to storage tanks at the top of a building, and water then drops down to the plumbing fixtures).

In cities with municipal water supply systems, water is distributed through street mains at pressures varying at the main from about 50 psi (about 350 kPa) to about 70 psi (about 480 kPa). For low-rise buildings of two or three stories, these pressures are adequate to act against the static pressure of water standing in the vertical piping, overcome the frictional resistance of water flow in the pipes, and still deliver water at the pressure required to operate plumbing fixtures. The flow pressure required at fixtures varies from 5 to 20 psi (35 to 138 kPa), depending on the type of fixture—for example, a basin faucet, showerhead and faucet, or water closet. (Table 19.14 in Section 19.11 lists minimum flow rates and pressures for typical plumbing fixtures.)

(a) Static Pressure

The pressure exerted at the bottom of a stationary "head" of water is related directly to its height. One cubic foot of water weighs 62.4 lb. Consider a "cube" of water 1 ft square and 1 ft high—its weight (62.4 lb) rests on a bottom area of 1 ft^2 (144 in^2). The static pressure at the bottom is $62.4/144 = 0.433$ psi (3 kPa). Reciprocally, 1 psi of pressure will *sustain* a static (stationary) column of water $1/0.433 = 2.3$ ft in height. (In SI units, 1 m of head = 10 kPa.) When fixture pressure and pressure lost in friction-of-flow in pipes are considered, the problem becomes more complex. Example 19.6 in Section 19.11 illustrates this problem in the calculation of pipe size. For upfeed and downfeed distribution, the relationship of heights and static pressure is one controlling design factor.

(b) Upfeed Distribution

In small, low buildings of moderate water demand, it is seldom difficult to achieve the proper flow pressure at fixtures by the use of an upfeed system. Pressure at the fixtures is usually more than required. When this causes an inconvenient splash, as at lavatory basins, a flow restrictor can be used in the faucet outlet.

Consider the typical upfeed system shown in Fig. 19.52, beginning at the point where supply water enters the building. In cold climates, water in the service entry pipe must not freeze. The pipe must therefore be below the *frost line* of frozen ground. This could vary from 0 to 7 ft (0 to 2 m), depending upon the geographical location. The onset of winter in cold climates requires the closing and draining of

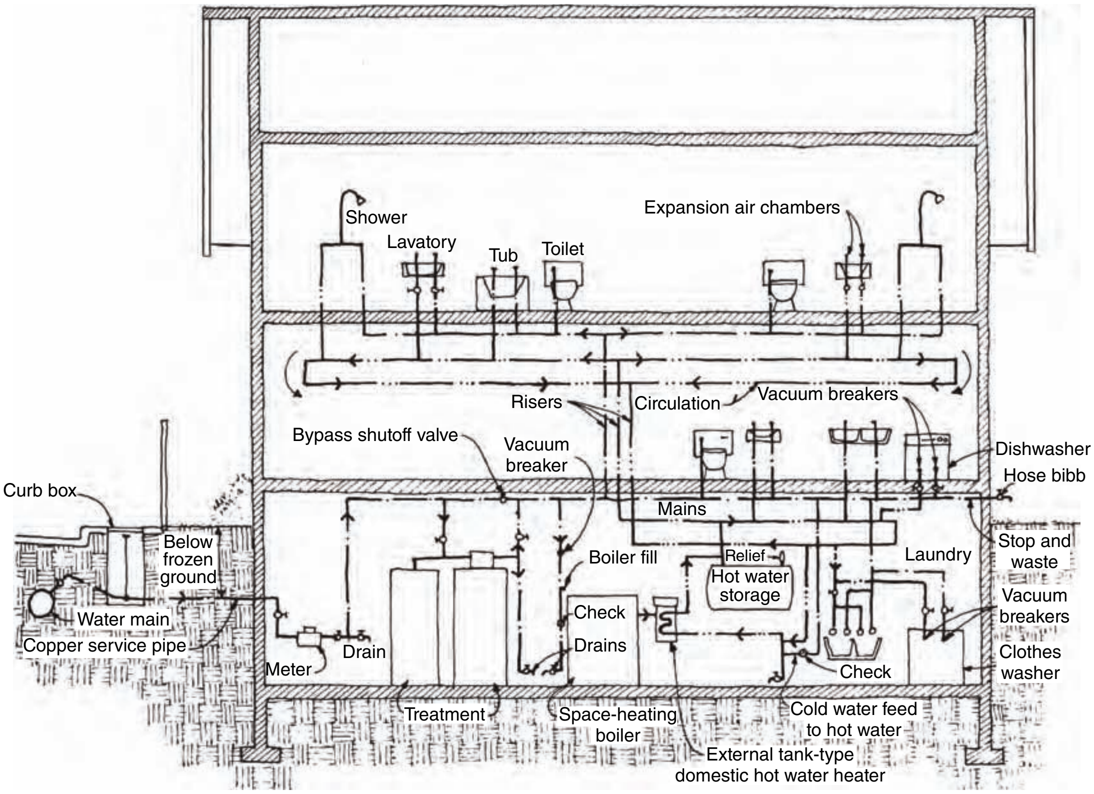


Fig. 19.52 *Upfeed water distribution using pressure in street mains. A schematic section of the water services in a typical residence.*

pipes supplying the hose bibbs (and other external piping) by means of a *stop-and-waste* valve. Houses left *unheated* in cold-winter weather must be entirely free of water that could freeze and burst the pipes. Note the drain valve at every low point in the system. House shutoff controls are usually located at the main, at the curb, and within the house.

Meters have recently taken on a new role: Along with measuring the water quantity for which the occupant is to be charged, they now sometimes serve a restrictive function. During water shortages, they can be used to indicate water use in excess of established limits, beyond which fines are imposed and, in some cases, the water supply reduced by valves controlled by the water company.

In-house treatment is often performed to reduce water hardness that could clog piping and equipment or to neutralize acidity—a source of corrosion. During the short periods when the treatment tanks are valved off for backwashing or other servicing, the *bypass shutoff valve* is opened.

From this point on, the water continues under pressure to

1. Supply makeup water to the space-heating boiler, as required
2. Supply water to and pressurize the cold water mains and branches, including the garden hose bibbs
3. Supply water to and pressurize the domestic hot water system through the hot water heater, the hot water storage tank, and the mains, branches, and circulating lines

The air-filled expansion chambers on cold water *runouts* absorb and reduce the shock of *water hammer*—the force exerted by decelerated flowing water that shakes and rattles pipes when faucets are shut off abruptly. On hot water runouts they perform the same function, as well as allowing for the expansion of the hot water as it increases in volume with increasing temperature. Vacuum breakers prevent backflow of polluted water into pipes carrying potable (hot or cold) water. Water from all fixtures and appliances, such as dishwashers, clothes washers, and boilers, is thus isolated.

Figure 19.52 shows all parts lying in a two-dimensional plane. In a real building, such a system is three-dimensional. For instance, economy of piping would suggest that, if possible, the kitchen and lavatory, as well as the two upstairs bathrooms, should be placed back-to-back.

(c) Principles of Downfeed Distribution

Water pumped directly from the street main (or from a basement "suction tank" filled by gravity from the main) is lifted to a roof-storage tank. In cold climates, the water in an outdoor tank is kept at temperatures above freezing by heating coils in the tank. The fact that water pressure increases with distance below the tank water level is suggested by the construction of the tank (shown in Fig. 19.53). The iron rings, tensioned by adjustable threaded clamps, become more closely spaced toward the bottom of the tank, where the greater water pressure makes it increasingly difficult to restrain the vertical wooden staves of this cylindrical barrel.

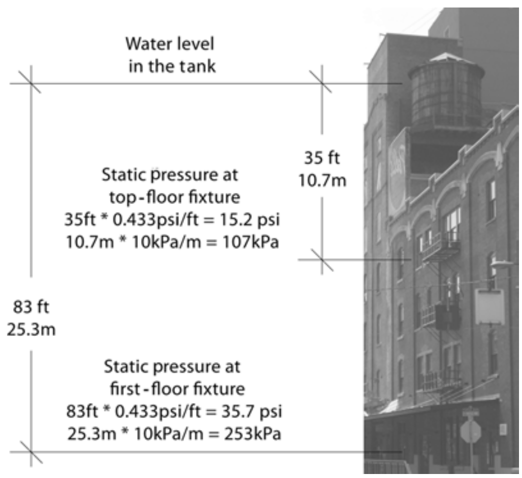


Fig. 19.53 *Mid-rise building with gravity downfeed distribution. Although upfeed distribution from a street main is possible in buildings higher than two or three stories, when street main pressures drop below the usual 50 psi (345 kPa), combined with heavy use, very low pressure results in fixtures in the upper stories. Therefore, water is pumped from the main to elevated roof tanks placed high enough to ensure reasonable pressure at the top story and ample pressure at the bottom of the downfeed run.*

Tanks like these add interest, though perhaps not beauty, to a building's silhouette. A view-blocking screen enclosing this tank would have to be about 24 ft (7.3 m) high. Architecturally, such a rectangular lump on the roof would not be much of an improvement. Yet in the century following the appearance of buildings such as shown in Fig. 19.53, our technology has become more complex. Presently, for most high-rise buildings, including many 60 stories and more in height, an entire rooftop crowded with equipment and technical facilities is needed to serve the stories below (or the uppermost *zone* of a building). The items could include

Water storage tanks
Two-story penthouses over elevator banks
Chimneys and/or flues
Numerous plumbing vents
Exhaust fans
Air-conditioning cooling towers
Cantilevered rolling rig to support a scaffold for exterior window washing
Perimeter track for a window-washing rig
Photovoltaic modules and/or solar thermal collectors

Thus, since the 1960s, tall buildings commonly have a *band* or *screen* two stories (or more) high above the structural roof. The best view locations are thus consigned to mechanical equipment. It might be said that it all began with the need for elevated water storage tanks.

(d) Tall Building Downfeed Distribution

Figure. 19.54*a* shows a medium-rise building in which one elevated tank can serve all of the lower floors. For taller buildings, it is advisable to separate groups of floors into *zones* with a maximum height (for plumbing pressure limits) of about 150 ft (about 45 m). This zone-height limitation is based upon the height-to-static pressure relationship. At the top of the zone (about 35 ft [10 m] below the storage tank), the minimum desirable pressure is probably at least 15 psi (103 kPa). At the bottom of the zone, the maximum desirable pressure is perhaps 80 psi (552 kPa); above this pressure, damage to fixtures might occur.

$$80 \text{ psi} - 15 \text{ psi} = 65 \text{ psi difference}$$
$$65 \text{ psi} \times 2.3 \text{ ft/psi} = \text{about } 150 \text{ ft}$$

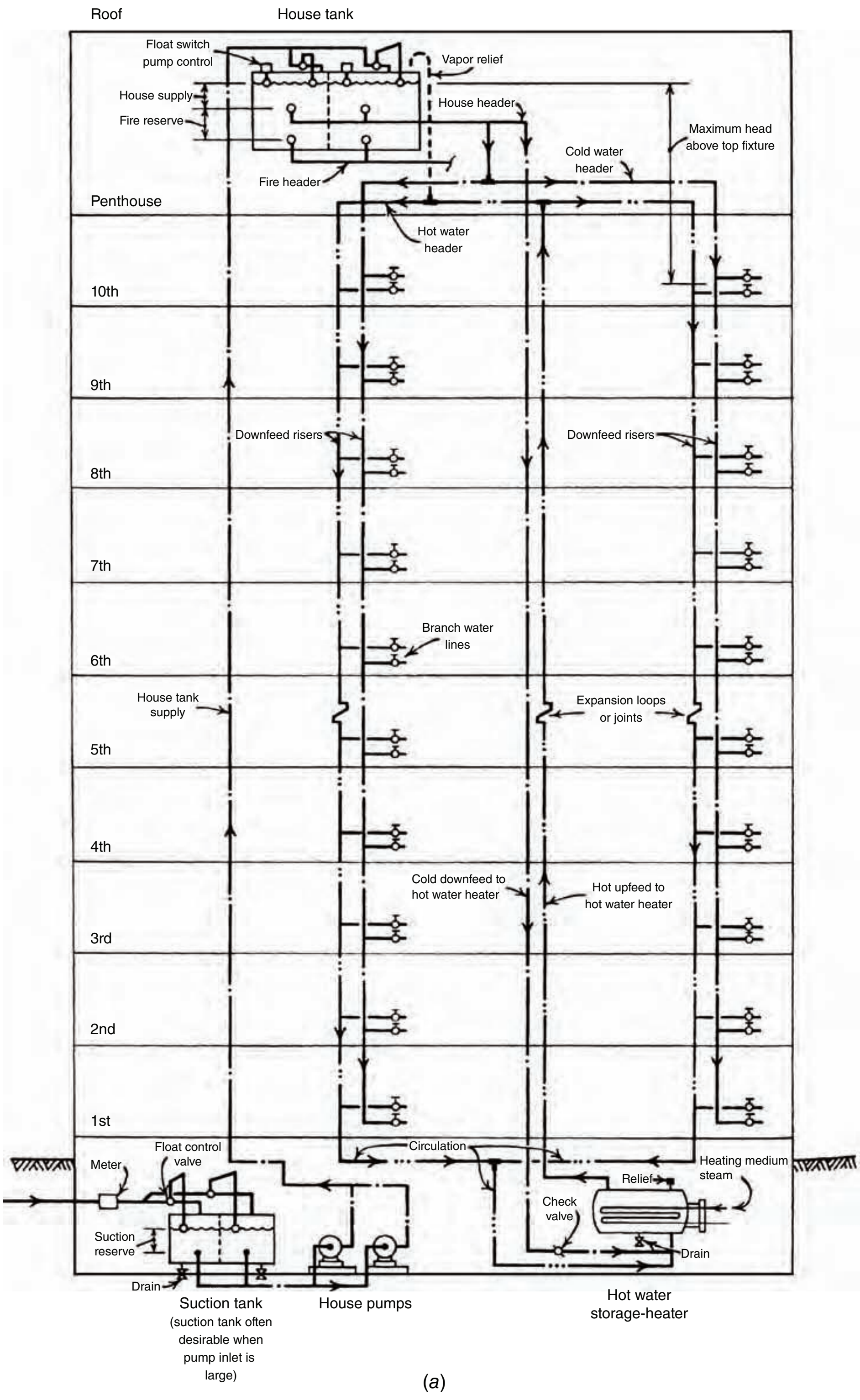
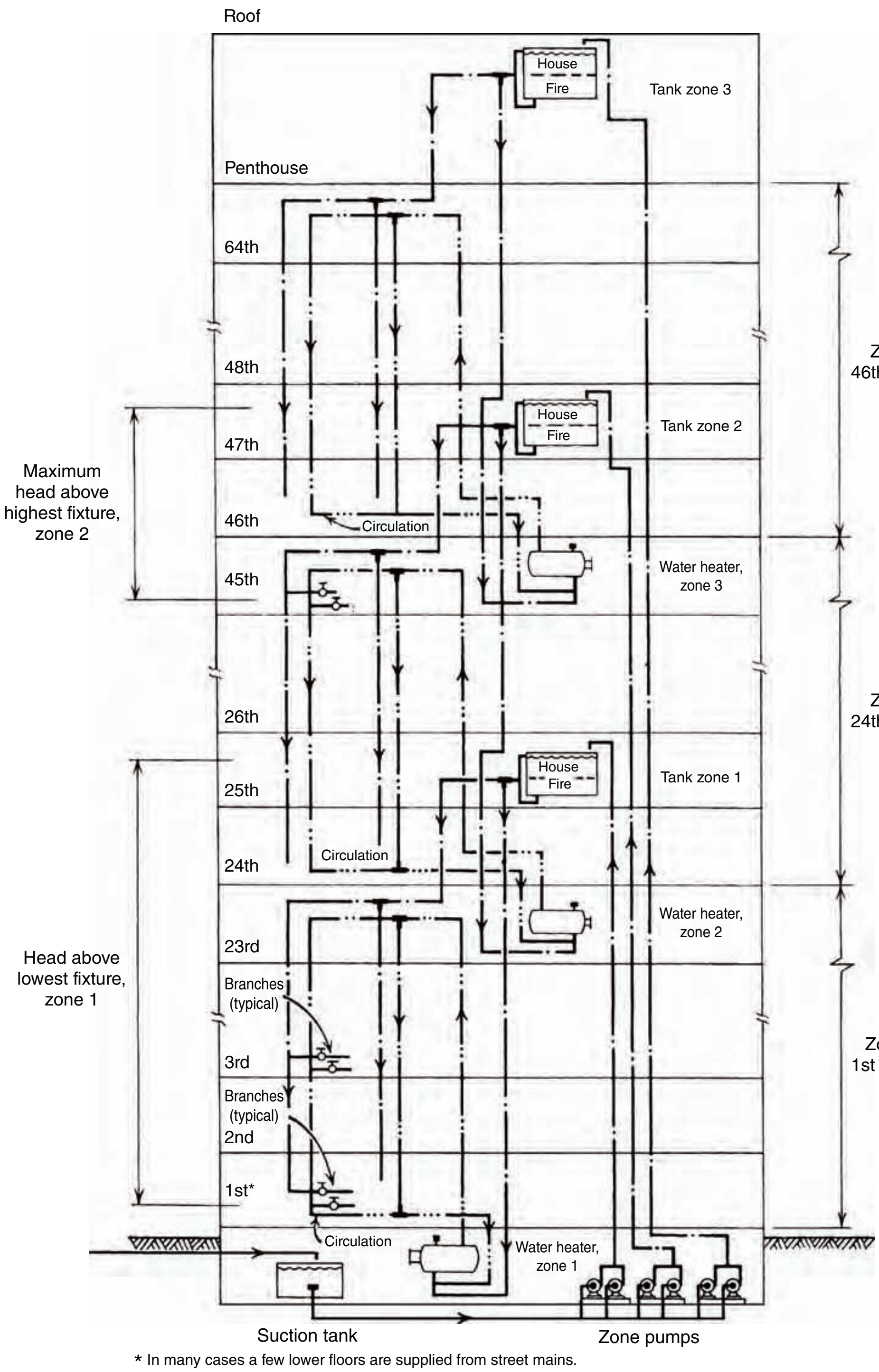


Fig. 19.54 *(a) Downfeed water distribution, schematic section, part of the water services for a 10-story building. Hot water circulation moves from the hot upfeed in two directions at the hot water header, then down to the tank through the two downfeed hot water risers. For details of one type of steel house tank, a typical centrifugal house pump, expansion joints, and expansion in the hot water riser, see Figs. 19.55 and 19.56. (b) Downfeed water distribution, schematic section, part of the water services for a much taller zoned building. Zone tanks include a fire reserve, but standpipes are omitted from this drawing. For details of the steam-type domestic water heater, see Fig. 19.24.*



(*b*)

Fig. 19.54 *(Continued)*

In SI units:

552 kPa − 103 kPa = 449 kPa difference
449 kPa × 0.1 m/kPa = about 45 m

With pressure-reducing valves at lower floors, however, these zones can be much higher, as shown in Fig. 19.54*b*.

Consider the system described in Fig. 19.54*a*, beginning with the elevated tank. The lower part of the tank often serves as a reserve space to hold a supply of water for a fire-extinguishing system. In this case, only the water in the upper part is available for use as domestic (service) water. The amount stored must be enough to supplement what the pump will deliver during the several daily hours of high demand that occur in most buildings. The pump then continues, often for several hours, to replenish the house supply that has become partially depleted during the busy period. The suction tank is a buffer between the system and the street mains. It usually holds enough reserve to allow the pumps to make up the periodic depletion in the house tank. It refills automatically by flow from the street main that, consequently, will not suffer as much of a drop in pressure as it would if it were connected directly to the suction side of the house pumps. Neighboring water users are protected from the adverse effects of sudden demands within adjacent large buildings (Fig. 19.55).

House tanks and suction tanks are sometimes made of steel plate and divided vertically in half, each half having identical piping and controls. Hence, one-half of the tank can be cleaned out at a time of low demand without shutting down the entire system. One full-capacity pump is supplemented by an equivalent standby pump for alternate use. Because there is no suction lift below the pump, or any fixture pressure at the top of the house tank supply, the head against which the pump works is the sum of the distance from the suction tank water level to the top of the house tank and the feet of head equivalent to the friction loss in the tank supply pipe. For this kind of service, the vertical piping is on the order of 3 or 4 in. (76 or 102 mm) in diameter for large buildings. Sizes are established by formal calculations.

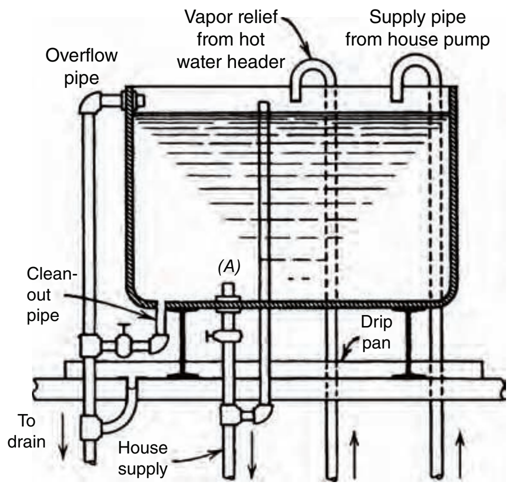
The house supply is fed by a short pipe from the house header to the cold water header that circles the top story and connects to many downfeed cold water risers. For simplicity, Fig. 19.54*a* shows only two risers and also omits many valves and controls.

Figure 19.54*b* is even more simplified. The circulating hot water originates as cold water at the house tank header, then takes quite a long route, descending to the bottom of the hot water heater, rising to seek its own level at the hot water header, and becoming available there for hot water downfeed on demand. All of this occurs as flow below the general pressurizing effect of the house tank. In effect, when there is a cold- and hot-water demand on a story near the top of the building, the cold water makes a short trip down to the faucet, while the hot water goes through three vertical pipes instead of one.

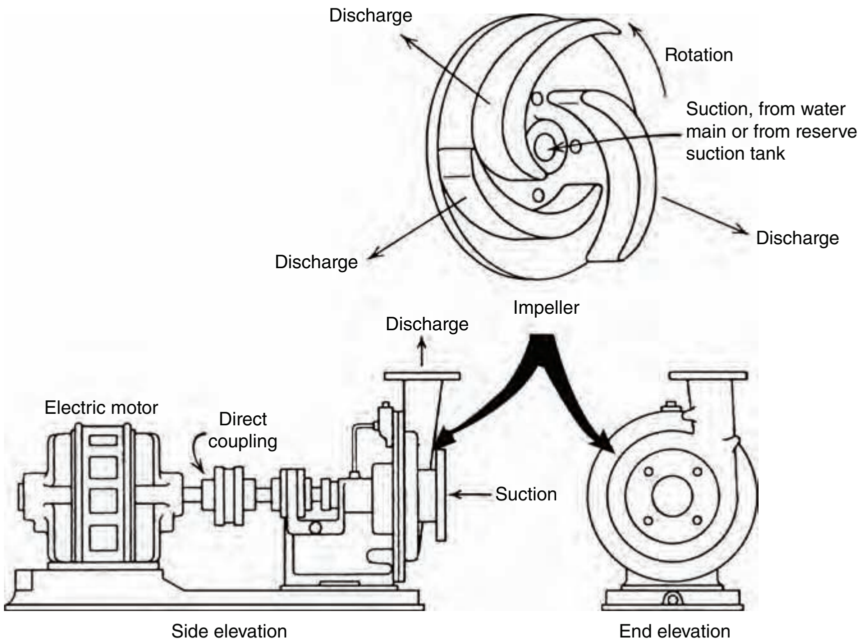
This arrangement, with tank above and heater below, is used in multiple forms for very tall buildings. The zones are quite independent; the only common service is that provided by the general suction tank. With this zoning method, problems of pipe expansion, large pipe sizes, and high pressures in lower stories are minimized. Commonly, 2½ stories, or about 35 ft (about 10 m), constitute the minimum pressure head above the top fixture served by any zone tank. The static pressure created at the fixture is thus 35 × 0.433 = 15 psi (10 × 10 = 100 kPa). If, during flow, not too much pressure is lost in friction, flushometers (flush valves) can be placed at this level, although flush tanks, because of their lower pressure demand, must often be accepted. The opposite problem occurs at the bottom of the zones, where excessive pressures must be reduced at the fixtures. In zone I of Fig. 19.54*b*, first-floor fixtures are below a head of 24½ stories, or about 149 psi (1027 kPa) of static pressure. Pressure-reducing valves must be used, and fixture control valves must be throttled.

(e) Pipe and Tube Expansion

The range of temperature experienced by hot water supply piping, from the normal indoor air temperature of about 70°F (21°C) to that of service hot water (which often exceeds 160°F [71°C]), can be 90F° (50C°), with resulting pipe expansion (Table 19.12). This longitudinal elongation of pipe, though negligibly small in houses, can be appreciable in a tall building. Two methods of allowing freedom for this longitudinal motion in long runs of expanding hot water piping are shown in Fig. 19.56*a*. These devices preclude the buildup of



(*a*)



(*b*)

Fig. 19.55 *(a) House tank in an elevated position for downfeed by gravity. Sediment in the tank is drawn off through the clean-out pipe and is prevented from entering the house water supply by the pipe projection at A. Water for fire reserve could be provided by additional piping or by a separate tank. (b) Centrifugal house pump, commonly used to fill an elevated house tank at the top story or at an intermediate mechanical floor. The electric motor responds to a float switch pump control at the tank.*

excessive stresses in the pipe material and the tendency of the pipes to buckle laterally.

EXAMPLE 19.5 A 20-story zone in a tall building has a height of 280 ft (85 m). What will be the increase in length of a copper tube carrying "service hot water" (DHW) when its temperature increases from 70° to 160°F (21° to 71°C)?

SOLUTION

The difference in temperature is 90F° (50C°). Approximate elongation per 100 ft for a 90F° increase is 1.01 in. (interpolating in Table 19.12).

TABLE 19.12 Thermal Expansion of Pipe

Temperature Increase		Approximate Expansion of Piping Material Inches per 100 ft (0.83 mm per m) of Length					
F°	C°	Carbon and Carbon Moly Steel	Cast Iron	Copper	Brass and Bronze	Wrought Iron	Plastic
20	11.1	0.15	0.15	0.22	0.22	0.15	0.5
40	22.2	0.3	0.3	0.44	0.44	0.3	1.1
60	33.3	0.45	0.45	0.67	0.67	0.45	1.7
80	44.4	0.6	0.6	0.89	0.89	0.6	2.4
100	55.5	0.76	0.7	1.12	1.12	0.76	3.3
120	66.7	0.91	0.84	1.35	1.35	0.91	4.3
140	77.8	1.07	1.0	1.58	1.58	1.07	5.3
160	88.9	1.22	1.13	1.81	1.81	1.22	6.2
180	100	1.38	1.27	2.04	2.04	1.38	—
200	111.1	1.55	1.4	2.27	2.27	1.55	—

$$\text{expansion} = 280 \text{ ft} \times (1.01 \text{ in./100 ft}) = 2.82 \text{ in.}$$

$$(85 \text{ m} \times (0.83 \text{ mm/m}) = 71 \text{ mm})$$ ■

There are a number of ways of providing for this expansion. The one shown in Fig. 19.56*b* accepts this motion at two locations, which would make the expansion in each case 1.41 in. Equidistant anchorage to fix the tubing is provided at the bottom, the 10th floor, and the 20th floor. The support of the vertical riser at floors other than those

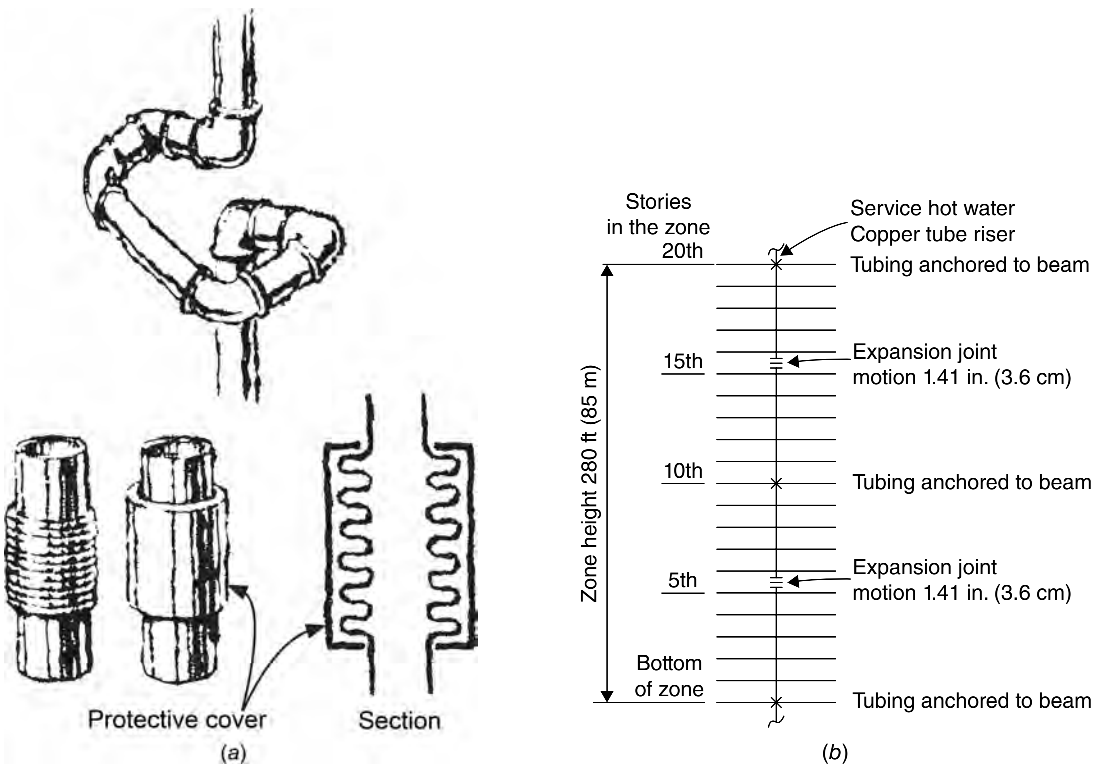


Fig. 19.56 *(a) Accommodation for the expansion of hot water piping or tubing.* Top: *Expansion joint of pipe and fittings.* Bottom: *A manufactured product in elevation and section. (b) Suggested scheme for location of the points of anchorage and expansion for service hot water tubing in a 20-story zone (Example 19.5).*

at which it is anchored could consist of clamps of the type illustrated later in Fig. 19.61, supported on springs.

(f) Pumped Upfeed Distribution

This distribution system (Fig. 19.57) is for medium-sized buildings—those too tall to rely on street main pressure but not so tall as to necessitate heavy storage tanks on the roof. The equipment associated with this system can deliver water at rates varying from those needed for two or three faucets to full building demand while maintaining at each outlet a pressure within 2 psi (14 kPa) of the design pressure for that outlet.

The installation shown in Figs. 19.57*a* and 19.57*b* uses a triplex pump group. According to demand, one, two, or three pumps will operate. Because each pump is of the variable-speed type, virtually an infinite number of delivery rates can be achieved within the zero to maximum design range. The pumps operate in sequence. When a very small rate of demand occurs, the smallest or "jockey" pump starts in response to a low voltage impressed on its motor. All operations are triggered and adjusted by the pressure sensor at the base of the riser. The jockey pump continues to run until it has reached its maximum delivery rate, at which time the first of the larger pumps cuts in, joined by the other larger pump when required. Sequential operation of the three pumps, each increasing in delivery as called for by the sensor, meets the requirement for an increasing supply at nearly constant pressure.

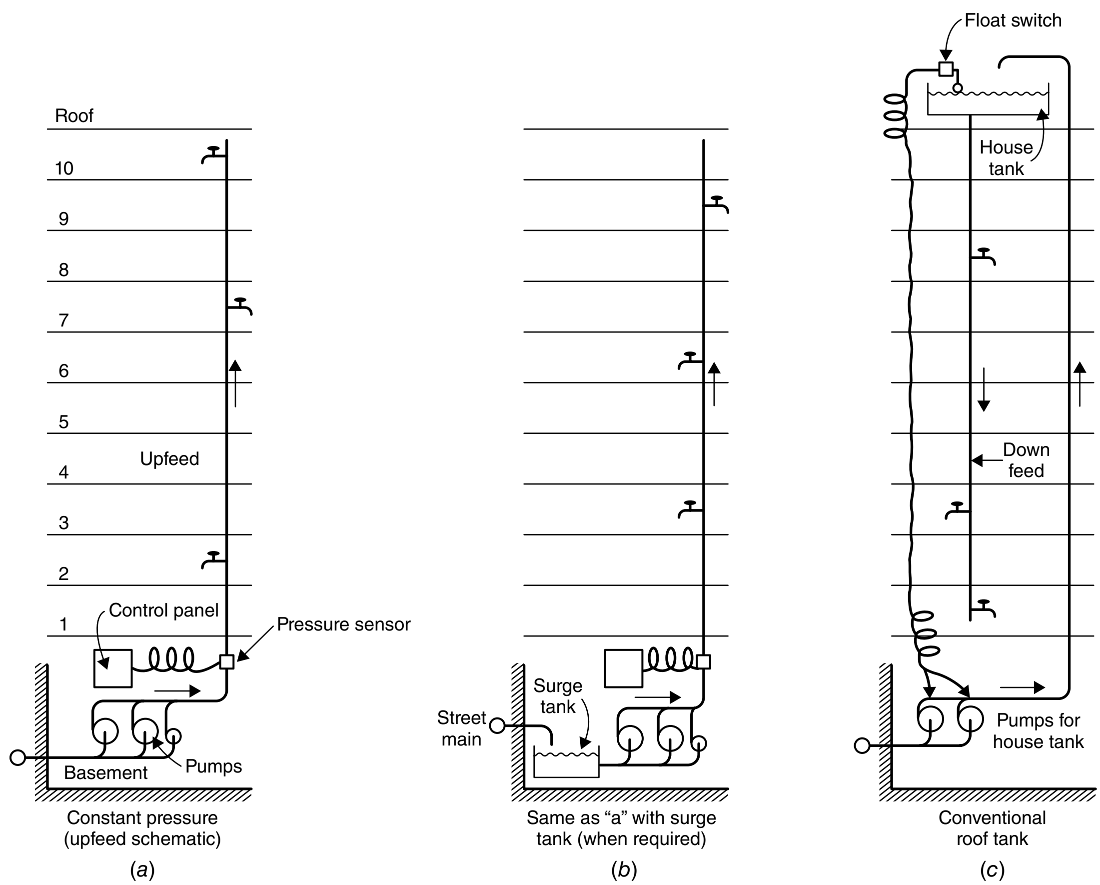


Fig. 19.57 *Constant-pressure upfeed pumping (a, b) compared to gravity downfeed from a house tank on the roof (c). (By permission of Progressive Architecture.)*

Wear on the two large pumps is equalized by the assigning of "lead" and "lag" positions. For a period of 24 hours, one of the large pumps holds the lead position and starts after the jockey pump, giving the other large pump a smaller burden. The next day the rested pump takes over the more active assignment. All of this occurs automatically.

At full operation, this triplex unit can put a suction demand on the street main that can seriously reduce the available water pressure in the neighborhood (Fig. 19.57*a*). Therefore, utilities sometimes require that such a system draw from a surge tank, filled by casual flow from the street main, independent of the building requirements (Fig. 19.57*b*). This requirement is often imposed when analysis indicates a maximum building demand in excess of 400 gpm (25 L/s).

Obvious advantages of upfeed pumping are elimination of the house tank and the heavier structure required to transmit its weight down to the footings, and elimination of the necessary periodic cleaning of the tank. A shortcoming is the lack of reserve storage, which could cause a serious problem during an electrical power failure. However, minimum flow during this kind of emergency can be arranged if a diesel or emergency standby motor is available to drive one of the pumps.

19.10 PIPING, TUBING, FITTINGS, AND CONTROLS

(a) Piping, Tubing, and Fittings

The system of water supply piping or tubing should efficiently fulfill its purpose, be easily maintained, and interfere as little as possible with architectural form and function. Except in basements, in utility rooms, and at points of access to controls, the piping system is usually concealed. Stud-and-joist construction can provide space for concealment, but in concrete or masonry buildings, vertical and horizontal furred spaces must often be provided.

Water supply piping is subject to corrosion over time. When pipe materials corrode, they first lose some carrying capacity (due to increased wall roughness and perhaps buildup of materials) and ultimately fail. Sediment from corrosion can adversely impact plumbing fixtures as well. Steel piping is particularly subject to corrosion. In the nonferrous group, red brass and copper tubing are effective in providing corrosion resistance. Copper tubing is less expensive than brass, assembles more easily, and is not subject to dezincification (attack by acids on the zinc in brass). For use in handling aggressive waters, plastic is often a good choice. Like copper, it is light in weight and assembles with great ease.

For ferrous pipes and "iron pipe size" brass, threaded connections are used. The external, tapered thread on the pipe is covered with pipe compound and screws tight against the internal tapered thread of a coupling or other fitting. The solder-joint connection in copper depends on capillary attraction that draws the solder into a cylinder of clearance between the mating surfaces of tube and fitting. This occurs after the surfaces are polished and fluxed and the parts placed in final position. They are then heated, and molten solder is applied to the circular opening where the fitting edge surrounds the tube, with a small clearance. Solder is then drawn into the cylindrical connection. Solders are often tin-antimony alloys. This kind of joint permits the advantageous setting up of an entire tubing assembly without turning the parts (as in threaded installations) and before the soldering commences. For the same strength, copper tubing may have thinner walls than threaded pipes because no threads need to be cut into it. Its smooth interior surface offers low friction to flowing water. Although threaded and solder-joint connections are the most common in small work, there are many other types (Figs. 19.58 and 19.59 and Table 19.13). Ferrous pipes in the larger sizes are often welded or connected by bolted flanges.

(b) Plastic Pipe

Most of the plastic pipes and fittings now produced are synthetic resins derived from such materials as coal and petroleum. These corrosion-resistant materials are widely used in water supply piping, fittings, and drainage systems (see Chapter 20). The National Sanitation Foundation (NSF) tests and certifies plastic pipe; the NSF seal must appear on pipes that are to carry potable water.

Most of the materials used for piping are thermoplastics and will repeatedly soften under the application of heat. PVDC (polyvinylidene chloride) material can carry water at 180°F (82°C), but

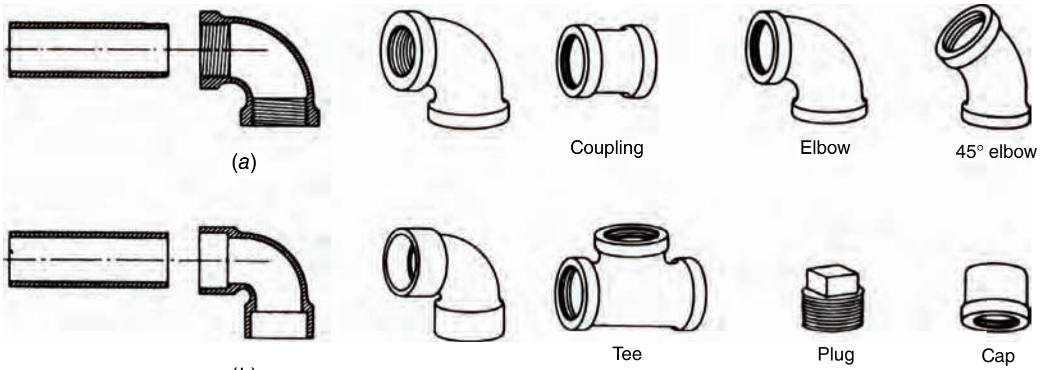


Fig. 19.58 *Methods of connecting pipes and fittings, and tubes and fittings. (a) Threaded: for ferrous pipe and fittings and for iron pipe size (IPS) brass. (b) Soldered: for copper tubing and fittings. A sliding fit similar to that of (b) is used for the solvent weld of plastic connections.*

plastic pipe should not be subjected to temperatures higher than this. Expansion (see Table 19.12) is much greater than that of other piping materials for the same Δt and affects the piping design. Shock-resistant plastic is used in the plumbing systems of most mobile homes.

(c) Valves and Controls

It is usually desirable to valve every riser, the branches that serve bathrooms or kitchens, and the runouts to individual fixtures. This facilitates repair at any location with a minimum of shutdown within a system. Water treatment equipment will have a valved bypass (see Fig. 19.52). Pumps and other devices that may need repair should be able to be disconnected by unions (Fig. 19.59) after valves are closed.

A gate valve (Fig. 19.60*a*), with a retractable leaf machined to seal tightly against two sloping metal surfaces when closed, offers the least resistance to water flow when open. It is usually chosen for locations where it is left completely open most of the time. The compression-type globe valve (Fig. 19.60*b*) is usually used for the closing or throttling of flow near a point of occasional use. Faucets are usually of the compression type, as are drain valves and hose connections. They are similar to an angle valve (Fig. 19.60*d*). When it is necessary to prevent flow in a direction opposite to that which is planned, a check valve (Fig. 19.60*c*) is introduced. The hinged leaf swings to permit flow in the direction of the arrow but closes against flow in the other direction.

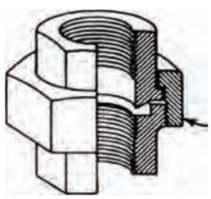


Fig. 19.59 *Example of threaded pipe fitting (a union) for ferrous or brass pipe. These and all common fittings are also available for solder–joint (copper) or solvent–weld (plastic) connections and usually for transition from one system or material to another.*

(d) Pipe Support

Water piping systems are heavy because of their water content and need regular support (Fig. 19.61). Vertical runs of piping should be supported at every story. Horizontal pipes should be supported at intervals of

6 ft (1.829 m) for ½-in. (12-mm) pipe
8 ft (2.438 m) for ¾-in. or 1-in. (19- or 25-mm) pipe
10 ft (3.048 m) for 1¼-in. (32-mm) or larger pipe

Although somewhat counterintuitive, these recommendations reflect the ability of a larger pipe to span greater distances between supports. Horizontal copper tubing should be supported at closer spacing than steel. Adequate positioning of horizontal runs is important to ensure correct

TABLE 19.13 Water Supply Piping Materials

PART A. WATER SERVICE ONLY[a]	
Material	**Connections[b]**
ABS (acrylonitrile butadiene styrene) plastic pipe	Mechanical with elastomeric seal (normally underground only); solvent cement; threaded joints
Asbestos–cement	Sleeve couplings of same material as pipe, sealed with elastomeric ring
Ductile iron water pipe	Mechanical Joints (see manufacturer)
PE (polyethylene) plastic pipe and tubing	Flared joints (see manufacturer), heat fusion, mechanical joints (see manufacturer)
PE-AL-PE (polyethylene/aluminum/polyethylene) pipe, PVC (polyvinyl chloride) plastic pipe	Mechanical with elastomeric seal (normally underground only); solvent cement; threaded joints (may reduce pressure rating)
PART B. WATER SERVICE AND DISTRIBUTION[c]	
Material	**Connections**
Brass pipe	Brazed, mechanical, threaded, or welded joints
CPVC (chlorinated polyvinyl chloride) plastic pipe (and tubing, indoors)	Mechanical (see manufacturer), solvent cement, or threaded joints (may reduce pressure rating)
Copper or copper-alloy pipe and tubing	Brazed, mechanical, soldered, threaded, or welded joints
Galvanized steel pipe[d]	Threaded or mechanical joints with an elastomeric seal
PB (polybutylene) plastic pipe and tubing	Flared joints, heat-fusion, or mechanical joints (see manufacturer)
PE-RT (polyethylene of raised temperature) plastic tubing	
PEX (cross-linked polyethylene) plastic tubing	
PEX-AL-PEX (cross-linked polyethylene/aluminum/cross-linked polyethylene) pipe	
PEX-AL-HDPE (cross-linked polyethylene/aluminum/high-density polyethylene)	
Stainless steel pipe	Mechanical, welded joints

Source: Reprinted from the 2012 *International Plumbing Code*, © International Code Council (ICC), Washington, D.C. All rights reserved. www.iccsafe.org

[a]Materials as listed in the 2012 *International Plumbing Code*. Water service piping is for an outdoor, underground connection from the building to the main or supply tank.

[b]Joints between different piping materials require approved adapter fittings; dielectric or brass converter fittings required between copper (or copper alloy) and galvanized steel piping.

[c]Materials as listed in the 2012 *International Plumbing Code*. Water distribution piping is within the building.

[d]Sediment from corrosion over the life of the pipe.

pitch and drainage. Hangers are adjustable for this purpose.

(e) Shock and Hot Water Expansion

Expansion chambers were shown diagrammatically in Fig. 19.52, and water hammer was explained in Section 19.9(b). Expansion chambers are often made of capped lengths of vertical pipe about 2 ft (0.6 m) long at the fixture branches (Fig. 19.62*a*). They trap air, which absorbs the impact of the water surge. A somewhat better (more controllable) device is a *rechargeable air chamber* (Fig. 19.62*b*). By closing the valve and draining the water through the hose bibb while the petcock above is open to admit air, the chamber may be refilled with air. Closing the petcock and hose bibb and opening the valve complete the service operation and reconnect the device with the water system. Rechargeable chambers (instead of pipe extensions) are used on branch lines adjacent to groups of fixtures. Access for service must be provided. Perhaps the best device is the special shock absorber (Fig. 19.62*c*).

Air cushions also protect the water heater tank's relief valve against frequent operation, with the resultant leakage of hot water, as hot water periodically expands and contracts in closed systems.

(f) Condensation or "Sweating"

The moisture that is always present in air can condense on the exterior surface of a cold pipe.

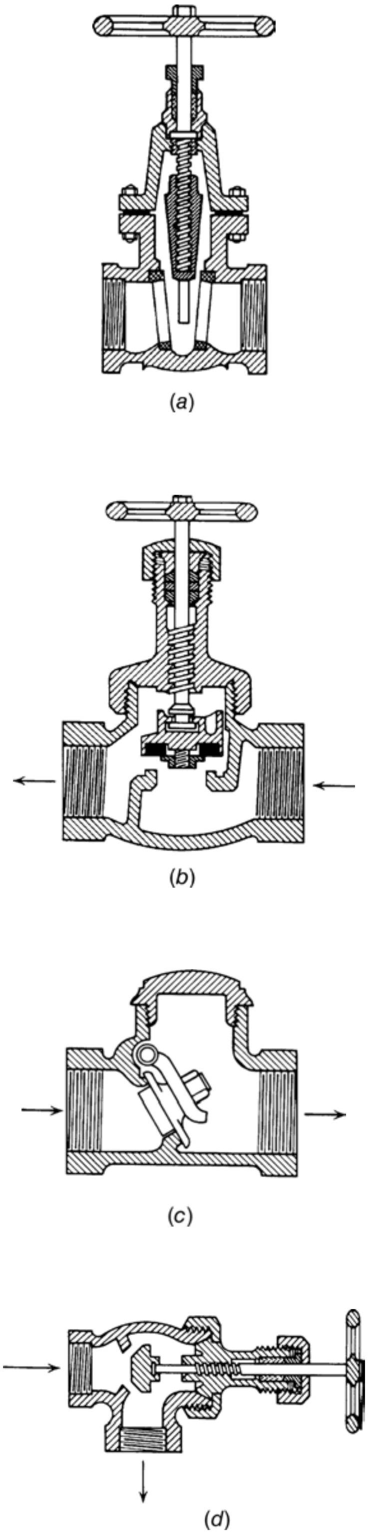


Fig. 19.60 *Typical valves for water systems. (a) Gate valve. (b) Globe valve. (c) Check valve. (d) Angle valve.*

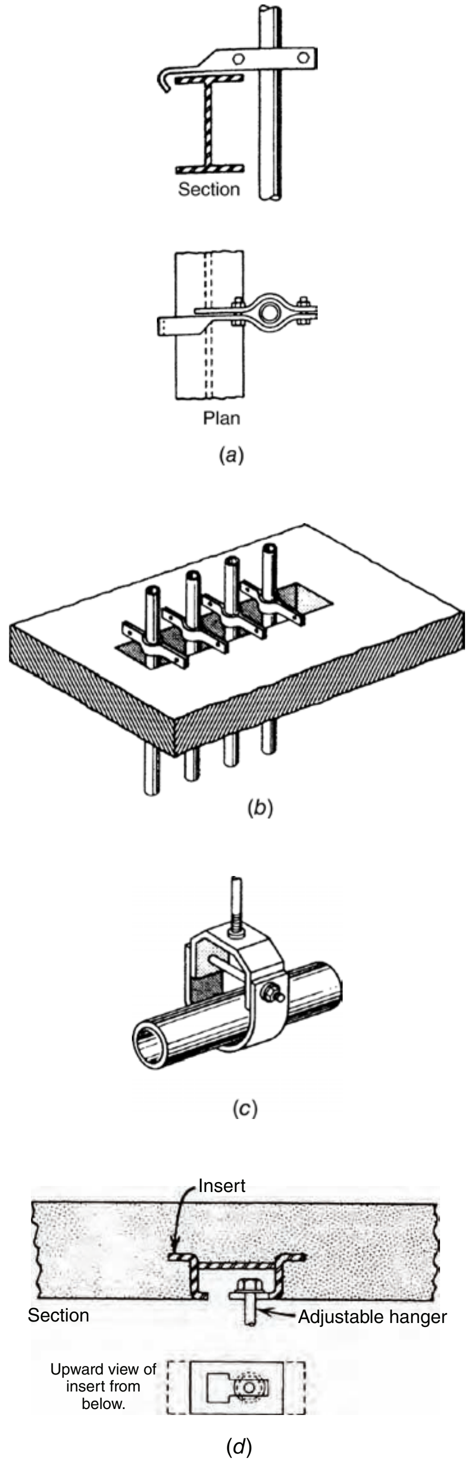


Fig. 19.61 *Pipe supports. (a) Vertical riser supported at a steel beam. (b) Vertical riser group supported at a slot in a concrete slab. (c) Horizontal pipe hung from a slab above by an adjustable-length clevis hanger. (d) Typical metal insert in a concrete soffit to receive the hanger rod.*

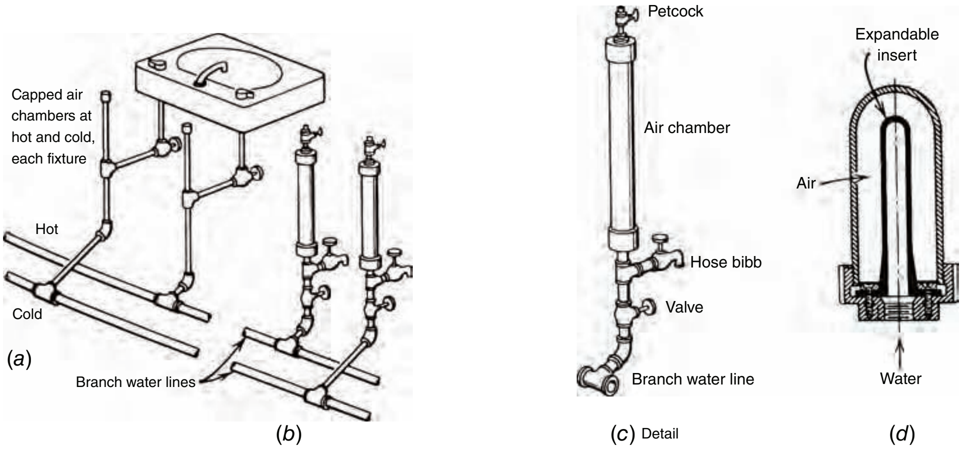


Fig. 19.62 *Shock relief and expansion chambers. Air chambers cushion the shock of the water hammer when the fixture faucets are shut off abruptly. They also permit hot water to expand instead of periodically forcing open the hot water emergency pressure relief valve at the heater or tank. (a) Capped air chambers at each supply pipe of each fixture. (b, c) Rechargeable air chambers on hot and cold branch water lines (individual fixture chambers are omitted when these are used). (d) Special shock absorber.*

Dropping off a pipe, it can create an unpleasant wet condition, disfigure finished surfaces, and provide conditions amenable to mold growth. Groundwater in some parts of North America is 50°F (10°C) and colder (see Fig. 10.31). A pipe carrying such water might have a surface temperature of about 60°F (15°C). The psychrometric chart (Appendix G) indicates that at a summer air temperature of 85°F (29°C), condensation will occur on such a pipe when the relative humidity exceeds 40%. To avoid condensation damage, all cold-water piping and fittings should be insulated. Glass fiber ½ to 1 in. (12 to 25 mm) thick is commonly chosen for this purpose. A tight vapor retarder on the exterior surface of the insulation prevents water vapor from penetrating the insulation and reaching the cold surface. The insulation provides another important advantage: It retards heat flow from the warmer air to the water, thus preventing the water from becoming disagreeably warm.

(g) Heat Conservation

Pipes carrying domestic hot water should be insulated to conserve energy used to heat the water and to ensure a correct water temperature at the points of use. Parallel hot and cold water piping, even though insulated, should be separated to prevent heat exchange. The pipe insulation should have a $k = 0.22 - 0.28$ Btu in./h ft^2 °F, and its thickness should be a minimum of ½ in. (on pipes less than 1½-in. diameter) or 1 in. (on pipes 1½-in. diameter and above). In SI units, $k = 0.032 - 0.040$ W/m K, and the thickness should be a minimum of 1.3 mm (on pipes less than 25-mm diameter) or 2.5 mm (on pipes 25-mm diameter and above).

Storage tanks and water heaters are usually manufactured with integral insulation. Older devices, however, may have less insulation than today's energy concerns warrant. As a result, many older water heaters are retrofitted with added insulation. Some electric utilities find the savings from conservation so attractive (relative to the cost of building new generating facilities) that they provide water-heater wrapping as a free service to customers.

19.11 SIZING OF WATER PIPES

There must be sufficient pressure at fixtures to assure the user of a prompt and adequate flow of water. Municipal ordinances often state that the flow must be adequate to keep the fixtures clean and sanitary. These convenience and sanitation objectives result in prescribed pressures that must be maintained at the various fixtures to ensure the proper flow rates listed in Table 19.14.

Minimum fixture pressures vary from 4 to 20 psi (28 to 138 kPa) for fixtures other than hose

TABLE 19.14 Flow and Pressure to Typical Plumbing Fixtures

	Minimum		
Fixture Served	**Flow Rate gpm (L/s)**	**Pressure psi (kPa)**	**Maximum Flow Rate or Quantity**
Bathtub	4 (0.25)	20 (138)	
Bidet	2 (0.13)	20 (138)	
Combination fixture	4 (0.25)	8 (55)	
Dishwasher, residential	2.75 (0.17)	8 (55)	
Drinking fountain	0.75 (0.05)	8 (55)	
Hose bibb	5 (0.32)	8 (55)	
Laundry tray	4 (0.25)	8 (55)	
Lavatory, private	2 (0.13)	8 (55)	2.2 gpm at 60 psi (0.14 L/s at 414 kPa)
Lavatory, public	2 (0.13)	8 (55)	0.5 gpm at 60 psi (0.03 L/s at 414 kPa)
Lavatory, public, metering or self-closing	2 (0.13)	8 (55)	0.25 gallon (0.95 L) per metering cycle
Shower head	3 (0.19)	8 (55)	2.5 gpm at 80 psi (0.16 L/s at 551 kPa)
Shower head, temperature controlled	3 (0.19)	20 (138)	2.5 gpm at 80 psi (0.16 L/s at 551 kPa)
Sink, residential	2.5 (0.16)	8 (55)	2.2 gpm at 60 psi (0.14 L/s at 414 kPa)
Sink, service	3 (0.19)	8 (55)	2.2 gpm at 60 psi (0.14 L/s at 414 kPa)
Urinal, valve	12 (0.76)	25 (172)	1.5 gallons (5.7 L) per flushing cycle[a] or 1.0 gallon (3.8 L) per flushing cycle
Water closet, blow out, flushometer valve	25 (1.58)	45 (310)	4 gallons (15 L) per flushing cycle[a]
Water closet, siphonic, flushometer valve	25 (1.58)	35 (241)	4 gallons (15 L) per flushing cycle[a] or 1.6 gallons (6 L) per flushing cycle
Water closet, tank, close coupled	3 (0.19)	20 (55)	1.6 gallons (6 L) per flushing cycle
Water closet, tank, one piece	6 (0.38)	20 (138)	1.6 gallons (6 L) per flushing cycle

Source: Reprinted from the 2012 *International Plumbing Code*, © International Code Council (ICC), Washington, D.C. All rights reserved. www.iccsafe.org

[a]The higher maximum listed is for public use in places of assembly, and for patients, inmates, and residents in hospitals, nursing homes, sanitariums, prisons, asylums, and reformatories.

bibbs. Because the pressure in street mains is usually about 50 psi (345 kPa), it is possible to ensure the minimum fixture pressure, provided that the water does not have to be lifted to too great a height and not too much pressure is lost by friction in distribution piping. Excessive friction results from piping that is too long in *developed length* (actual distance of water flow) or that interposes too many fittings (such as elbows and tees), or is too small in diameter.

The pressure losses in an upfeed system served by street main pressure are as follows. For A in the following chart, use the highest, most remote fixture from the main.

Minimum fixture flow pressure	A
Pressure lost because of height	+ B
Pressure lost by friction in piping	+ C
Pressure lost by flow through meter	+ D
Total required street main pressure	= E

During design, items A, B, and E are known and are reasonably constant. A value for A can be found in Table 19.14. Street main pressure, E, is a characteristic of the local water supply and is obtained from the water utility. Item B, the pressure lost due to height, can be found by multiplying the height in feet by 0.433 (height in meters by 10) (see the discussion of static head in Section 19.9*a*). Item D, the pressure lost in flow through the water meter, depends upon flow and pipe size (Fig. 19.63), neither of which is yet known. Therefore, the value of item D is *estimated*. (For residences and small commercial buildings, meter size rarely exceeds 2 in. [50 mm].) Later, it must be checked and a recalculation made if necessary. This leaves one unknown, the value of C, where

$$C = E - A - B - D$$

Pipe size is based upon Fig. 19.64. Pipe diameter is determined by the point of intersection of a horizontal line representing flow and a vertical line expressing friction loss. To select a pipe size, one needs to know the probable flow and the *unit-friction loss* in the pipe and fittings. The noise created by water flow also must be considered. Flow above 10 fps (3.1 m/s) is usually too noisy; flow

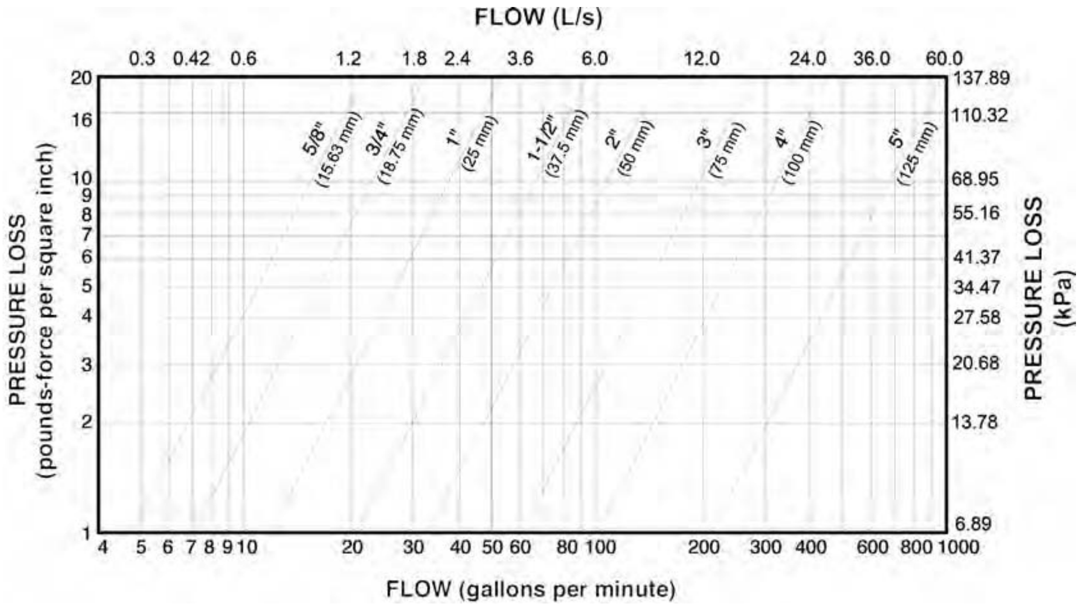


Fig. 19.63 *Pressure losses in disk-type water meters. (©2012* Uniform Plumbing Code*; Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.)*

above 6 fps (1.8 m/s) may be too noisy in acoustical-critical locations.

Flow can be found for any pipe by first listing all fixtures to be served by that pipe, assigning them water supply fixture units (WSFU, listed in Table 19.15), and finding the total WSFU. This total is then converted to the likely demand flow in gpm from Fig. 19.65*a* (demand flow in L/s from Fig. 19.65*b*). These curves show that actual flow does *not* increase in direct proportion to an increase in fixture units. The larger an installation, the less likely that many fixtures will be operating concurrently. This reflects the statistical concept known as *diversity*.

To establish the desired friction loss, divide value C (pressure lost by friction in piping) by the *total equivalent length* of the piping. This length is the sum of the *developed length* (total linear distance of water travel) and the length equivalent of the fittings. For example, Table 19.16 shows that, in a 1-in. (25-mm) diameter pipe run, a 90° ell causes a friction loss equivalent to that of 3 ft (0.9 m) of straight pipe. The number and style of fittings are estimated, and the size of fittings is assumed. This may be puzzling, but it is a common trial-and-error engineering procedure that sometimes requires several recalculations.

EXAMPLE 19.6 Using the following data—some of which have been arrived at by the assumptions referred to previously—find the proper size for a metered water supply main. (See Example 19.7 for SI units.)

Street main pressure (minimum)	50 psi
Height, topmost fixture above main	30 ft
Topmost fixture type	Water closet with flush valve (1.6 gal per flush)
Fixture units in the system	85 wsfu
Developed length of the piping (to the highest and most remote fixture)	100 ft
Pipe length equivalent to fittings (commonly estimated at 50% of the developed length)	50 ft
System uses predominantly	Flush valves

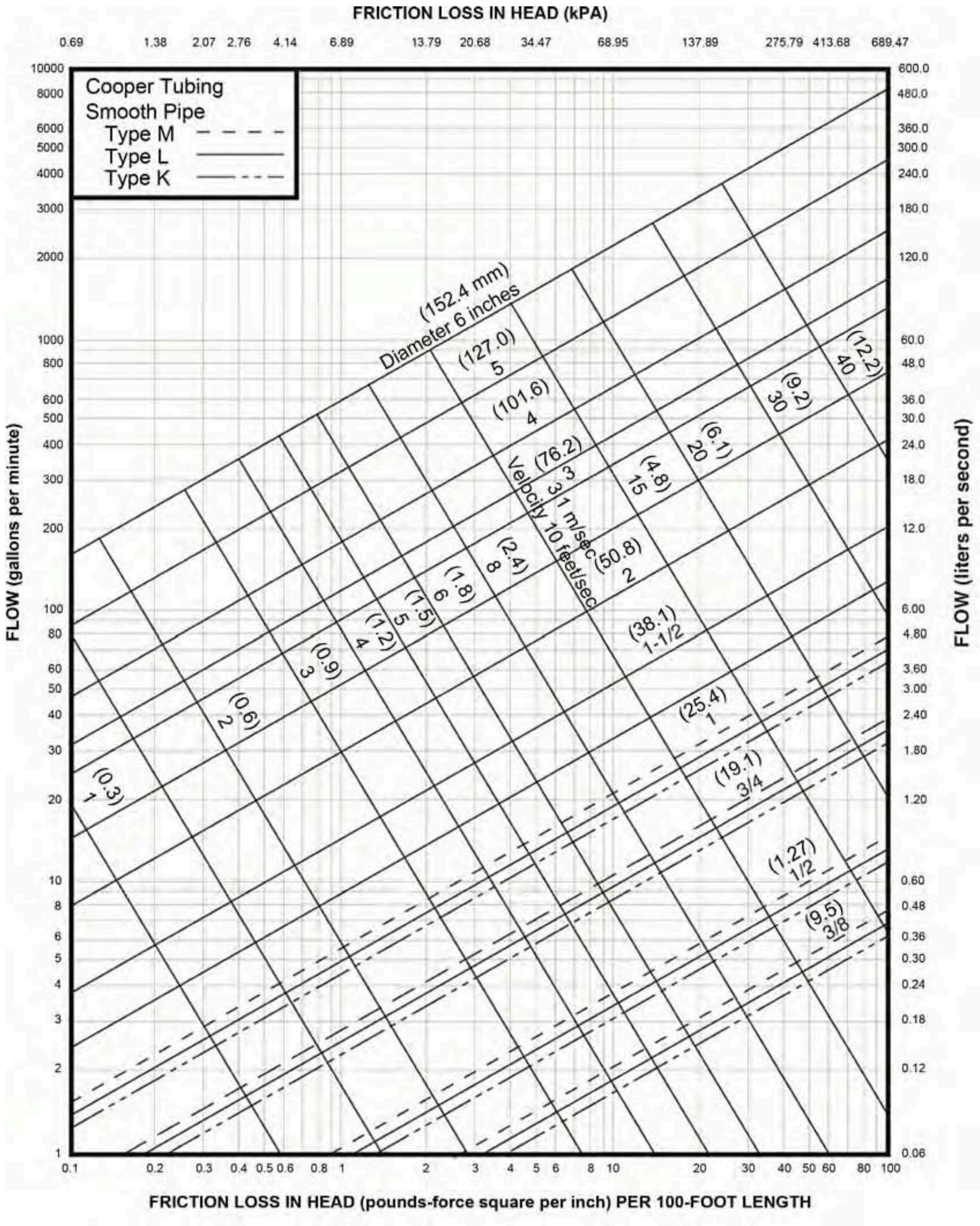


Fig. 19.64 Friction loss chart for smooth pipe. Velocity is shown to assist in noise control efforts: above 10 fps (3 m/s), moving water can be clearly heard within pipes. (©2012 Uniform Plumbing Code*; Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.)*

TABLE 19.15 Water Supply Fixture Units (WSFU)

			Load Values in WSFU		
Fixture	**Occupancy**	**Type of Supply Control**	**Cold**	**Hot**	**Total**
Bathroom group	Private	Flush tank	2.7	1.5	3.6
Bathroom group	Private	Flush valve	6	3	8
Bathtub	Private	Faucet	1	1	1.4
Bathtub	Public	Faucet	3	3	4
Bidet	Private	Faucet	1.5	1.5	2
Combination fixture	Private	Faucet	2.25	2.25	3
Dishwashing machine	Private	Automatic		1.4	1.4
Drinking fountain	Offices, etc.	⅜ in. (9.5 mm) valve	0.25		0.25
Kitchen sink	Private	Faucet	1	1	1.4
Kitchen sink	Hotel, restaurant	Faucet	3	3	4
Laundry trays (1 to 3)	Private	Faucet	1	1	1.4
Lavatory	Private	Faucet	0.5	0.5	0.7
Lavatory	Public	Faucet	1.5	1.5	2
Service sink	Offices, etc.	Faucet	2.25	2.25	3
Shower head	Public	Mixing valve	3	3	4
Shower head	Private	Mixing valve	1	1	1.4
Urinal	Public	1 in. (25 mm) flush valve	10		10
Urinal	Public	¾ in. (19 mm) flush valve	5		5
Urinal	Public	Flush tank	3		3
Washing machine, 8 lbs (3.6 kg)	Private	Automatic	1	1	1.4
Washing machine, 8 lbs (3.6 kg)	Public	Automatic	2.25	2.25	3
Washing machine, 15 lbs (6.8 kg)	Public	Automatic	3	3	4
Water closet	Private	Flush valve	6		6
Water closet	Private	Flush tank	2.2		2.2
Water closet	Public	Flush valve	10		10
Water closet	Public	Flush tank	5		5
Water closet	Public or private	Flushometer tank	2		2

Source: Reprinted from the 2012 *International Plumbing Code*, www.iccsafe.org

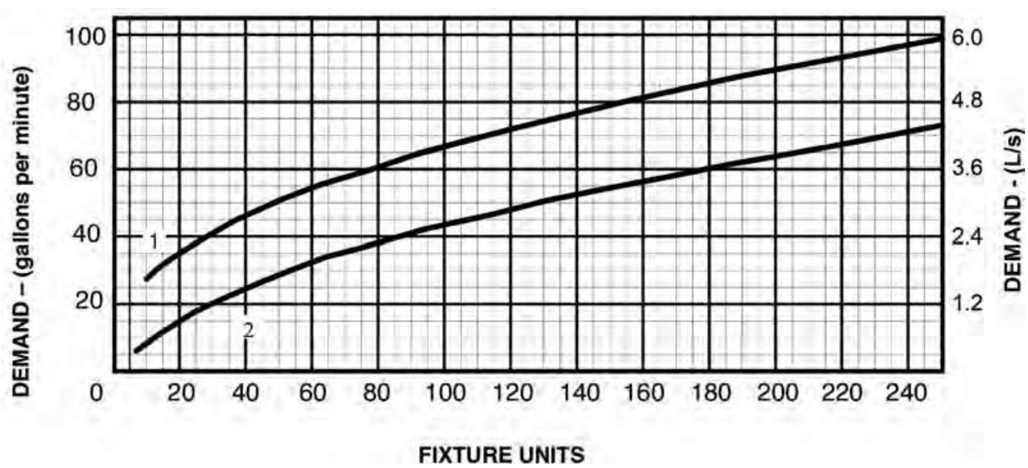


Fig. 19.65 *Estimating curves for flow based upon total water supply fixture units. Curve 1 is for a system with predominantly flush valves; curve 2 is for a system with predominantly flush tanks. For fixture unit totals above 250, see the 2012* Uniform Plumbing Code. *(©2012* Uniform Plumbing Code*; Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.)*

TABLE 19.16 Allowance in Equivalent Length of Pipe for Friction Loss in Valves and Threaded Fittings[a]

PART A. I-P UNITS

Diameter of Fitting (in.)	Equivalent Length of Pipe for Various Fittings						
	90° Standard Ell (ft)	45° Standard Ell (ft)	Standard Tee 90° (ft)	Coupling or Straight Run of Tee (ft)	Gate Valve (ft)	Globe Valve (ft)	Angle Valve (ft)
⅜	1	0.6	1.5	0.3	0.2	8	4
½	2	1.2	3	0.6	0.4	15	8
¾	2.5	1.5	4	0.8	0.5	20	12
1	3	1.8	5	0.9	0.6	25	15
1¼	4	2.4	6	1.2	0.8	35	18
1½	5	3	7	1.5	1.0	45	22
2	7	4	10	2	1.3	55	28
2½	8	5	12	2.5	1.6	65	34
3	10	6	15	3	2	80	40
3½	12	7	18	3.6	2.4	100	50
4	14	8	21	4.0	2.7	125	55
5	17	10	25	5	3.3	140	70
6	20	12	30	6	4	165	80

PART B. SI UNITS

Diameter of Fitting (mm)	Equivalent Length of Pipe for Various Fittings						
	90° Standard Elbow (mm)	45° Standard Elbow (mm)	Standard Tee 90° (mm)	Coupling or Straight Run of Tee (mm)	Gate Valve (mm)	Globe Valve (mm)	Angle Valve (mm)
9.5	305	183	457	91	61	2438	1219
12.7	610	366	914	183	122	4572	2438
19.1	762	457	1219	244	152	6096	3658
25.4	914	549	1524	274	183	7620	4572
32	1219	732	1829	366	244	10668	5486
38	1524	914	2134	457	305	13716	6706
51	2134	1219	3048	610	396	16764	8534
64	2438	1524	3658	762	488	19812	10363
76	3048	1829	4572	914	610	24384	12192
102	4267	2438	6401	1219	823	38100	16764
127	5182	3048	7620	1524	1006	42672	21336
152	6096	3658	9144	1829	1219	50292	24384

Source: ©2012 *Uniform Plumbing Code*; Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

[a]Based on nonrecessed threaded fittings. Use one-half of these allowances for recessed threaded fittings or streamline solder fittings.

SOLUTION

From the minimum street main pressure, subtract the sum of the fixture pressure, the static head, and the pressure lost in the meter. This sum is

	psi
A: fixture pressure (Table 19.14)	15
B: static head 30 ft × 0.433	13
D: pressure loss in meter (estimated, Fig. 19.63)	8
Subtotal	36
E: pressure in street main	50
(A + B + D)	–36
E – (A + B + D)	14

The pressure lost in 100 ft (developed length) of piping plus the 50 ft of piping equivalent to the pressure lost by friction in the fittings therefore can total 14 psi. Total equivalent length is 150 ft. This procedure ensures 15 psi at the critical fixture. The unit-friction loss, psi/100 ft of pipe, will be 14 psi × 100/150 (total equivalent length) = 9.33 psi/100 ft.

From Fig. 19.65*a*, curve 1, a flush-valve system with 85 WSFU will have a probable flow (diversified demand) of about 64 gpm. Given this information, enter Fig. 19.64*a* horizontally at 64 gpm and vertically at 9.3 psi/100 ft. At the intersection of these lines, the pipe diameter and velocity are determined. Between 1½-in.- and 2-in.-diameter pipe:

Velocity = 8 fps (less than 10 fps, so OK)

Therefore, a 2-in.-diameter supply pipe will be chosen with a 2-in. meter.

Now find the actual pressure loss in the 2-in. meter for a flow of 64 gpm. Figure 19.63*a* shows that this is about 4 psi. Because this is *less* than the 8 psi estimated, the pressure at the fixture will be slightly higher than the minimum needed. When a final system layout is made, the actual fittings are tabulated, and the equivalent length of fittings is found. If this differs greatly from the 50 ft estimated, a recalculation is made. ■

EXAMPLE 19.7 Solve the pipe sizing problem posed in the previous example using SI units.

Street main pressure (minimum)	345 kPa
Height, topmost fixture above main	10 m
Topmost fixture type	Water closet with flush valve
Fixture units in the system	85 WSFU
Developed length of the piping (to the highest and most remote fixture)	30 m
Pipe length equivalent to fittings (commonly estimated at 50% of developed length)	15 m
System uses predominantly	Flush valves

SOLUTION

From the minimum street main pressure, subtract the sum of the fixture pressure, the static head, and the pressure lost in the meter. This sum is

A: fixture pressure (Table 19.14)	103 kPa
B: static head 10 m × 10 kPa/m	100 kPa
D: pressure loss in meter (estimated, Fig. 19.63)	55 kPa
Subtotal	258 kPa
E: pressure in street main	345 kPa
(A + B + D)	−258 kPa
E − (A + B + D)	87 kPa

The pressure lost in 30 m (developed length) of piping plus the 15 m of piping equivalent to the pressure lost by friction in the fittings therefore can total 87 kPa. Total equivalent length is 45 m. This procedure ensures 103 kPa at the critical fixture. The unit-friction loss, kPa/100 m of pipe, will be

87 kPa × 100/45 (total equivalent length)
= 193 kPa/100 m

From Fig. 19.65*b*, curve 1, a flush-valve system with 85 WSFU will have a probable flow (diversified demand) of about 4 L/s. Given this information, enter Fig. 19.64*b* horizontally at 4 L/s and vertically at 193 kPa/100 m. At the intersection of these lines, the pipe diameter and velocity are determined. Between 38-mm- and 51-mm-diameter pipe:

Velocity = about 2.4 m/s (less than 3 m/s, so OK)

Therefore, a 51-mm-diameter supply pipe will be chosen with a 51-mm water meter. ■

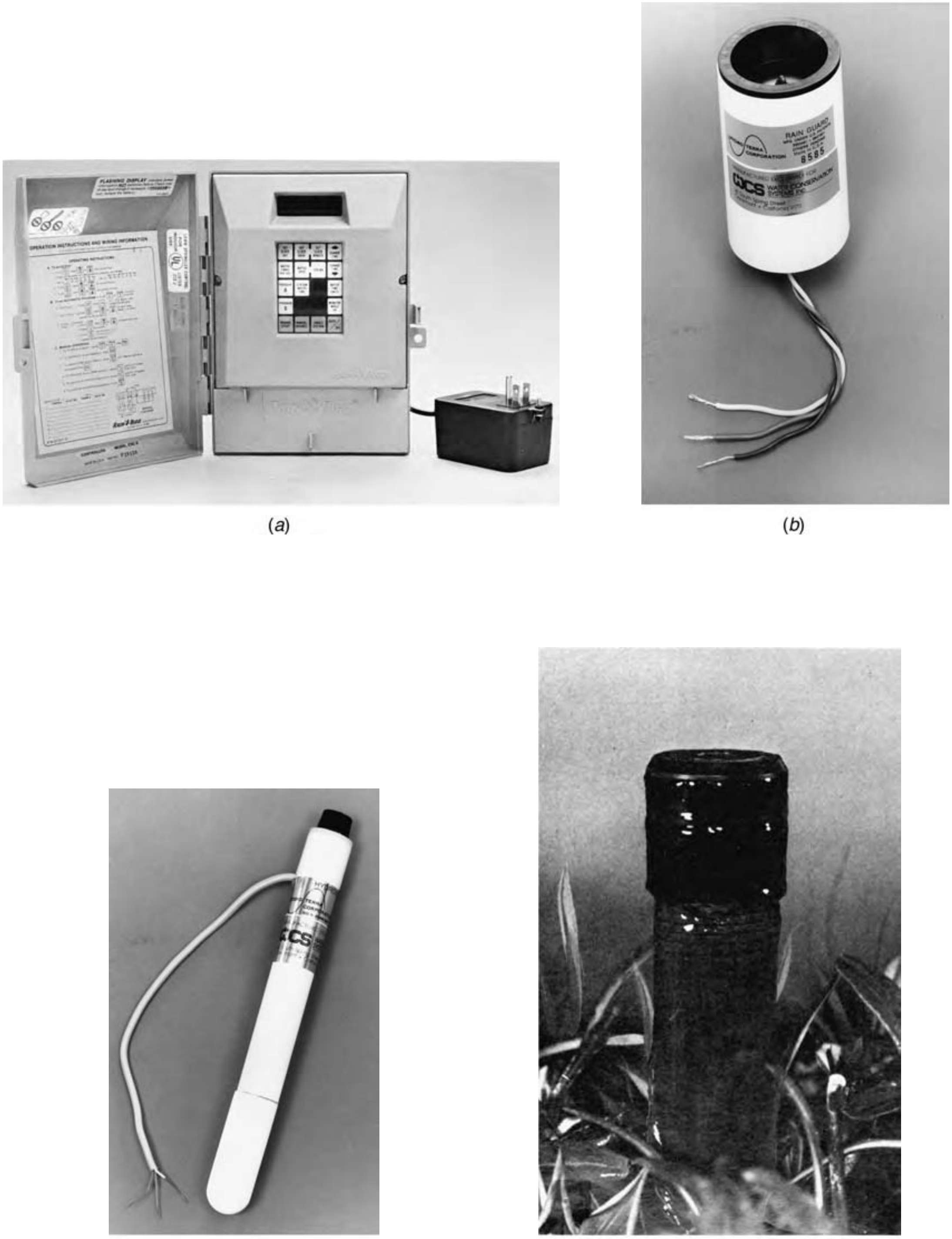
As in Example 19.6, the actual system pressures can be found using the exact pressure loss in a 51-mm water meter.

19.12 IRRIGATION

The highest design priority for landscape watering is to ensure optimum rainfall retention. In the past, provision for watering the landscape around buildings frequently was limited to the installation of hose bibbs at building exteriors. In many areas of North America, half of the residential water usage (see Chapter 20) is for outdoor purposes. With increasing demands on a finite water supply, water-conserving irrigation equipment has become available.

Lawn sprinklers are relatively inefficient irrigating devices, as much of their water is lost to evaporation and runoff. It is commonly estimated that lawn sprinkling will provide ½ in. of water per hour per square foot of lawn (or 0.3 gph per ft^2) (0.005 L/s per m^2).

Landscape sprinkling is least efficient during the daytime, when hot sun and dry air combine to increase the rate of evaporation. However, nighttime sprinkling is rarely convenient for building custodians or homeowners. One solution to this problem is the use of *sprinkler timing devices* (Fig. 19.66*a*), which control electronic valves and a network of underground supply pipes and sprinkler heads that are permanently installed within landscaped areas. These timing devices typically include controls governing the length of the watering cycle, the time at which the cycle begins (usually before sunrise, when relative humidity is highest), and the number of days between cycles. A "rainy day switch" is often included so that irrigation can be discontinued during rainy weather. Rain sensors can be used to shut



(a) (b) (c) (d)

Fig. 19.66 *Components for automatic landscape sprinkling systems. (a) Programmable controllers feature multiple stations, up to 14-day sequences, and memory provisions in case of power failure. (Courtesy of Rain Bird Sales, Inc.) (b) A solid-state rain sensor automatically prevents needless watering during rainfall. (c) A tensiometer controls irrigation by monitoring the moisture content of the soil. (Courtesy of Water Conservation Systems, Inc.) (d) Bubblers are low-flow substitutes for sprinklers—a step toward drip irrigation. These can be pressure-compensating to permit constant flow. (Courtesy of Rain Bird Sales, Inc.)*

off irrigation automatically (Fig. 19.66*b*). Tighter control over the water–plant relationship can be obtained with *tensiometers* (Fig. 19.66*c*), which monitor the moisture content of the soil at the depth of the plants' root zone. These can be installed so as to override the automatic timing device, thus watering more—or less—frequently, depending upon the plants' needs. Instead of sprinklers, *bubblers* (Fig. 19.66*d*) can be installed, with very low flow rates and less evaporative water loss.

Drip irrigation takes an approach very different from that of the flooding method typical of sprinklers. From a network of plastic tubes, either just underground or on the surface, *emitters* (Fig. 19.67) slowly and steadily drip water onto the ground surface at each needy plant. Most of this water soaks into the soil at a rate that is better for most plants than the sudden, short flooding of intermittent sprinkling. Two requirements are especially important for drip systems: The water must not contain materials that can clog the small holes of the emitters, and the pressure must be low. Pressure-reducing valves at the source of the drip system are advisable; if necessary, filters should also be installed there.

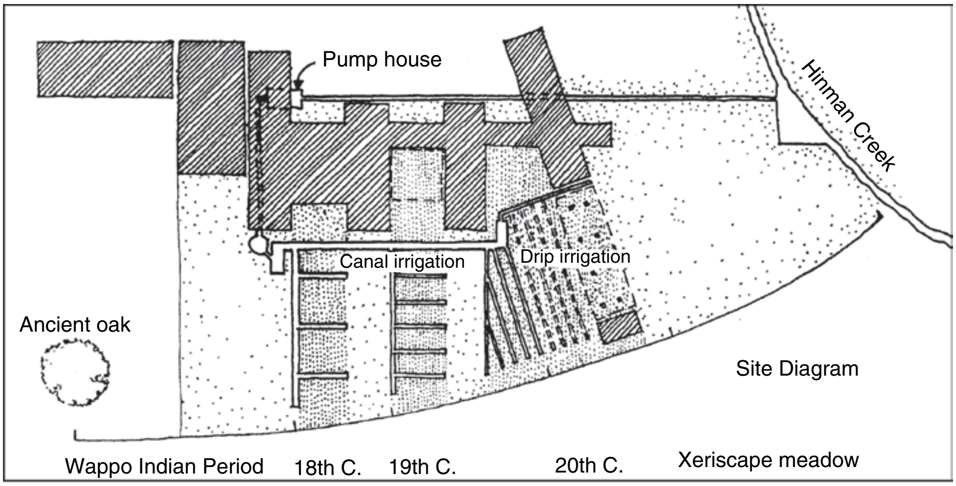
Drip irrigation is not a universal solution to landscape watering; it is best for individual plants such as shrubs and small trees but is difficult to apply to large lawns. Where appropriate, it can achieve significant water conservation compared to sprinklers. A detailed discussion of soil texture, moisture, and plant growth is provided in Lowry (1988, Chap. 4).

Recycled or reclaimed water for irrigation, often provided by graywater systems and sometimes by stored rainwater, is gradually gaining acceptance in North American building codes. This topic is explored further in Section 20.9. Considered nonpotable, this water must sometimes be deliberately colored and/or be accompanied by warning signs at each outlet.

Irrigation, past and future, shaped the design of the Napa Valley Museum in California (Fig. 19.68). An adjacent creek provides water behind a small dam. A pump house carries water to a central observation tower, where visitors see the history of irrigation

(*a*) (*b*)

Fig. 19.67 *Equipment for drip irrigation. (a) On low-pressure lines, emitters are installed—one for each group of plants to be watered. The lines can be laid on the ground surface or just under the surface. (b) Simple emitter boxes allow easy access. (Courtesy of Rain Bird Sales, Inc.)*



(*a*)

(*b*)

Fig. 19.68 *The Napa Valley Museum shows the history of irrigation in northern California. (a) Site plan. Water, piped from behind a small dam in the adjacent creek, flows through open canals, then provides drip irrigation, eventually discharging to a field of native plants. (b) The canals help guide the visitor through the exhibit gardens. (Courtesy of Fernau and Hartman, architects, Berkeley, CA.)*

displayed in the context of the Napa Valley. The path of water in this model landscape invites visitors to explore canal irrigation of the eighteenth and nineteenth centuries, as well as advanced drip irrigation and xeriscape plantings of the twentieth century and beyond. (Xeriscape planting, as a part of the hydrozone landscape concept, was shown in Fig. 18.21.)

References and Resources

ANSI. 1986. American National Standard for Buildings and Facilities A117.1-1986, *Providing Accessibility and Usability for Physically Handicapped People*. American National Standards Institute. New York, NY.

ASHRAE. 2011. *ASHRAE Handbook—HVAC Applications*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, GA.

Banham, R. 1969. *The Architecture of the Well-Tempered Environment*. Architectural Press. London.

Brown, G. Z., J. Reynolds, S. Ubbelohde. 1982. *InsideOut: Design Procedures for Passive Environmental Technologies*. John Wiley & Sons. Hoboken, NJ.

HUD. 1977. *Intermediate Minimum Property Standards Supplement*. U.S. Department of Housing and Urban Development. Washington, DC.

IAPMO. 2012. *Uniform Plumbing Code*. International Association of Plumbing and Mechanical Officials. Walnut, CA.

ICC. 2012. *International Plumbing Code*. International Code Council. Washington, DC.

Kira, A. 1976. *The Bathroom*, new and expanded ed. Viking Press. New York, NY.

Lowry, William P. 1988. *Atmospheric Ecology for Designers and Planners*. Van Nostrand Reinhold. New York, NY.

Milne, M. 1976. *Residential Water Conservation*. U.S. Office of Water Research and Technology, Department of Commerce, NTIS.

National Drinking Water Clearinghouse, *Tech Brief* Series: June 1996. *Disinfection*; September 1996. *Filtration*; February 1997. *Corrosion Control*; May 1997. *Ion Exchange and Demineralization*. U.S. Environmental Protection Agency. Washington, DC.

Plante, R. H. 1983. *Solar Domestic Hot Water: A Practical Guide*. John Wiley & Sons. Hoboken, NJ.

Reif, D. K. 1983. *Passive Solar Water Heaters*. Brick House Publishing. Andover, MA.

The United States Access Board (accessible design): www.access-board.gov/

U.S. Architectural and Transportation Barriers Compliance Board. *Americans with Disabilities Act (ADA) Accessibility Guidelines for Buildings and Facilities*. Washington, DC.

U.S. Environmental Protection Agency. 1975. *Manual of Individual Water Supply Systems*. US EPA. Washington, DC.

CHAPTER 20

Liquid Waste

AMONG OTHER ISSUES, CHAPTERS 18 AND 19 CONSIDERED the waste of resources inherent in the use of potable water to flush toilets. This chapter examines some consequences of this conventional approach to bodily waste removal, along with alternatives that use no water at all, and indeed that offer to convert waste to a useful resource. For typical U.S. residences, the potential impact of such alternatives on water usage and treatment is shown in Fig 20.1

Almost every plumbing fixture within buildings is provided with both water supply and waste pipes. Because the toilet is usually the largest user of water (Fig. 20.1), as well as one of the worst water polluters, this chapter begins with recycling/waterless alternatives to the flush toilets and urinals that were discussed in Section 19.7. Then, more conventional systems using water to move waste, and conventional treatment systems from individual to large-scale, are discussed. Discussions of graywater and storm water treatment complete this chapter.

20.1 WATERLESS TOILETS AND URINALS

The array of waterless alternatives includes toilets in which chemicals or oil are substituted for water. These devices are commonly found in airplanes, vehicles, and boats, as well as in remote and environmentally sensitive areas. The chemicals must be frequently recharged and the waste products removed. Other waterless toilets temporarily treat the waste awaiting discharge to a sewer by freezing it, burning it, or otherwise packaging it so that it remains inoffensive. Such devices can become energy-intensive approaches to waterless waste disposal. Also, they are still dependent upon public sewer systems.

(a) Composting Toilets

Once considered too unconventional to ever gain mainstream acceptance, these ecologically attractive devices are now appearing not only in

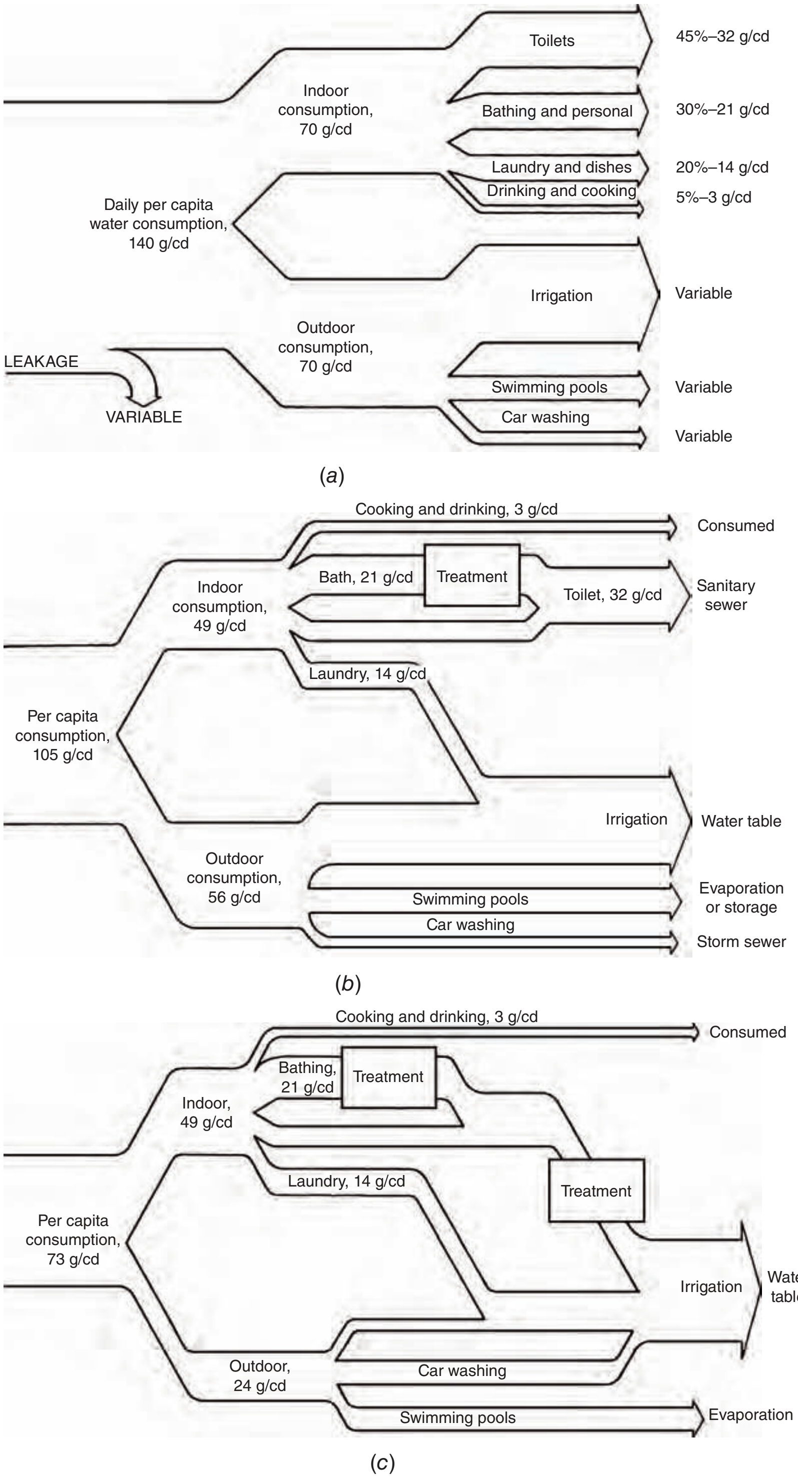


Fig. 20.1 *Opportunities for water conservation for the typical U.S. family. (a) At present, the average U.S. residential usage is about 140 g/cd (gallons per capita per day) [530 L/cd; liters per capita per day]—all of it potable. (b) With attention to recycling and the matching of water quality to requirements, potable water usage could be cut to 105 g/cd (397 L/cd)—a 25% reduction. (c) With further on-site treatment and recycling, potable water usage drops to 73 g/cd (276 L/cd)—a 40% reduction—and the need for public sewage treatment (for residences) disappears. (From Milne, 1976.)*

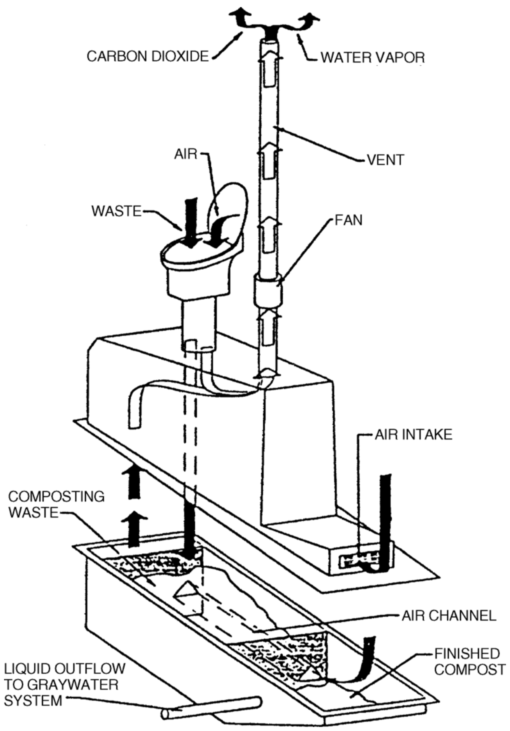


Fig. 20.2 *Composting toilets save water and eliminate the need for a sewer connection. They are used at the C. K. Choi Building, University of British Columbia, Canada, where the toilet rooms are concentrated near the center stairs, with a small basement below containing composting chambers and a rainwater cistern for irrigation. The composting toilets produce both dry humus (nutrient rich soil) and a liquid outflow to a graywater recycling system. (Courtesy of Matsuzaki Wright, architects, Vancouver, BC.)*

homes, but also within institutional buildings (Fig. 20.2). Perhaps several generations needed to pass between regular use of the historic outhouse and use of these modern composting toilets, before widespread acceptance could be observed. They offer a self-contained and low-energy strategy for providing waterless toilets. Wherever water supplies are unreliable, or waste discharge is difficult or prohibited, composting toilets offer an alternative. Silent and immune from potential water damage (freezing pipes or overflows), these systems rely upon *aerobic* digestion of waste (i.e., that which occurs in the presence of oxygen). By and large, aerobic systems are essentially odor-free, and the exhaust air they produce is rich in CO_2 (not necessarily good) and water vapor (harmless). In contrast, *anaerobic* decomposition (i.e., that which occurs without oxygen) is malodorous and produces methane gas as a key by-product. See Sections 20.7 and 20.8 for more about methane and anaerobic decomposition.

Waste material deposited in composting toilets builds up in a mound, which retards the flow of air for decomposition. Wood shavings are commonly added with each use to encourage toppling of the mound and to add some carbon to the resulting compost. Some composting toilets include a means of regular mechanical stirring of the compost chamber, aiding aerobic decomposition.

Ventilation is important, both to reduce odors and to facilitate evaporation of excess moisture. A ventilation stack is an essential feature; it is often assisted by a very small (3- to 5-W) fan. Problems with insects hatching within the composting chamber can be lessened by keeping vegetable scraps out of the chamber, as they are frequent sources of insect eggs.

The C. K. Choi Building at the University of British Columbia (Fig. 20.2) eliminated a connection to the city sewer system by implementing a combination of composting toilets and a graywater treatment system. The composting toilets in this three-story, 30,000-ft^2 (2787-m^2) facility for the Institute of Asian Research are estimated to save 1500 gal (5680 L) of water per day. At an estimated 30,000 uses per year, the environmental impact of this composting system is significant. The liquid end product will be added to the graywater treatment system at the rate of about 3 to 5 gal (11 to 19 L) per day. The composting chambers are located in a small basement below the toilet rooms at the center of the building.

The graywater includes waste from lavatories and sinks, as well as liquid from the composting toilets. This water drains into a subsurface "graywater trench" containing a variety of phragmite plant material. The roots support microbial life that is known for digesting and neutralizing bacteria. This graywater is then used for irrigation. Graywater systems are discussed further in Section 20.9.

(b) Vault-Type Composting Toilets

The *Clivus Multrum system* (Fig. 20.3) has a large decomposition chamber that must be below the toilet (and perhaps also the kitchen), from which it

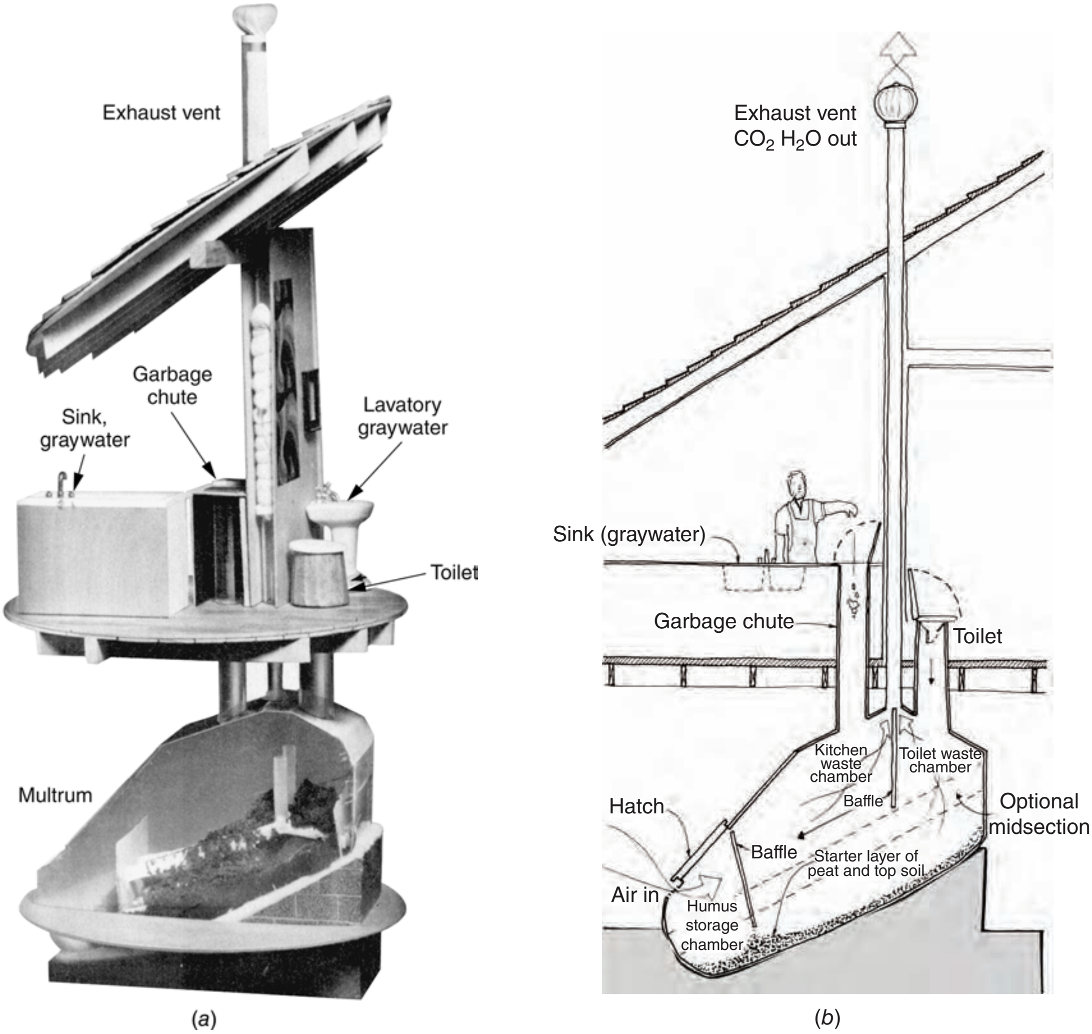


Fig. 20.3 *Clivus Multrum system, with composting of both kitchen and toilet organic wastes. (a) The lower composting chamber requires 4 ft × 8 ft × 7 ft (1.2 m × 2.4 m × 2.1 m) of floor space, a generous supply of air (warm air speeds decomposition), and access for periodic removal of the garden-ready humus. (b) It must be arranged so that its upper end receives toilet wastes; as the bottom slopes downward, kitchen wastes are deposited on top of the decomposing toilet wastes. The vent stack ensures continuous airflow, preventing odors from entering bathroom or kitchen. The toilet seat and cover must be kept closed when not in use to keep air flowing through the composting chamber and out of the stack. The toilet bowl (containing no water) swings open when the seat is occupied, exposing the composting chamber below. (Courtesy of Clivus Multrum USA, Inc.)*

readily accepts organic waste. It must also be accessible from the ground floor in order to remove the humus—varying between 3 to 10 gal (11 to 38 L) of soil per person per year.

The relatively large chamber (about the size of a Volkswagen "bug") and its low position/access requirement can have a significant impact on design. Also of significance is the device's appetite for fresh air. The more air it has, the speedier the process of aerobic decomposition and, therefore, the less odor. In winter, this air flow could cause increased heat losses in a building via infiltration. The natural ventilation due to the stack effect is at least 15 cfm (7 L/s) in the Clivus Multrum. A ventilating fan in the stack will increase this rate significantly. However, if outdoor air is brought directly to the chamber, it could be too cold for proper decomposition; a chamber temperature of

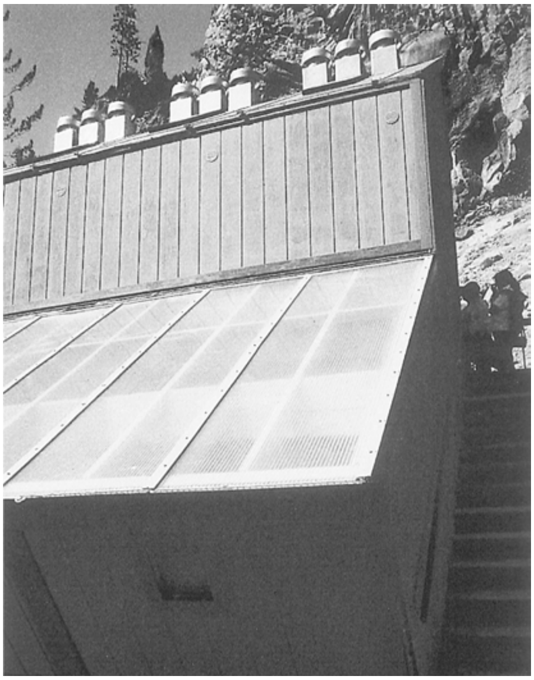


Fig. 20.4 On the shore of Crater Lake, Oregon, a building with three Phoenix composting toilets serves visitors. An attached sunspace contains and warms the composting chambers and contains an evaporator for liquid waste. The facility is closed all winter.

98°F (37°C) is optimum. Solar heating of input air offers one alternative. However, adding too much heat to compost piles encourages oxidation rather than aerobic decomposition; inferior compost results.

Another composting toilet application is shown on the shores of Oregon's Crater Lake National Park in Fig. 20.4. Consider the challenge: This facility is at the bottom of a 1-mile trail down from the crater rim; public sewers are miles away and hundreds of feet higher in elevation; severely cold winters and deep snow close the trail for more than half of the year; and Crater Lake is one of the clearest in the world, so water pollution is absolutely to be avoided. Three Phoenix composting toilet tanks sit within a solar-heated attached sunspace.

The *Phoenix* composting tanks (Fig. 20.5) feature rotatable tines that speed aerobic decomposition. They also can be fitted with an evaporation system, typically using a small photovoltaic (PV) driven pump that delivers liquid to the top of a drip tank filled with plastic balls. This establishes a very large surface area, and a small fan also aids evaporation.

(c) Heater-Type Composting Toilets

Another approach puts the composting chamber within the toilet itself. The more compact the composting chamber, the more likely that heat must be added to speed decomposition and to evaporate liquid. Although electricity provides an easy and compact way to heat, using such high-quality energy to treat waste reduces the compact toilet's ecological advantage.

In the most compact of *Sun-Mar*'s products (Fig. 20.6), a variable-diameter Bio-drum is turned by a fold-out hand crank at the front of a rather conventional-looking toilet. At this size, it is rated for continuous residential use by one adult or a family of two (or for weekend/vacation use, by three adults or a family of four). Sun-Mar uses a three-chamber approach, separating the quick composting of waste and toilet paper, the evaporation of liquid, and the safe storage of the finished compost.

(d) Waterless Urinals

Urine is often kept out of composting toilets for several reasons. First, excess liquid in the chamber creates a discharge issue, complicating an otherwise simple end result of occasional harvesting of garden-ready humus. Second, urine is nearly sterile and an excellent fertilizer, and its separate capture could be useful. If not captured, urine can be directed either to a graywater or to a wastewater system.

Waterless No-Flush™ urinals utilize a floating layer of BlueSeal® liquid that forms a barrier to sewer vapors but allows urine to readily pass through (Fig. 20.7). This liquid does not dissolve, mix, or react chemically with urine. It is more than 95% biodegradable and does not evaporate at 100°F (38°C). Because 1 quart (0.9 L) of this liquid lasts for 15,000 to 20,000 urinal uses, it replaces an estimated 15,000 to 60,000 gal (56,780 to 227,120 L) of water that would have been used by conventional flush urinals. The trap retains sediments and should be emptied occasionally, and the liquid is periodically replenished (3 oz [89 mL] per 1500 uses).

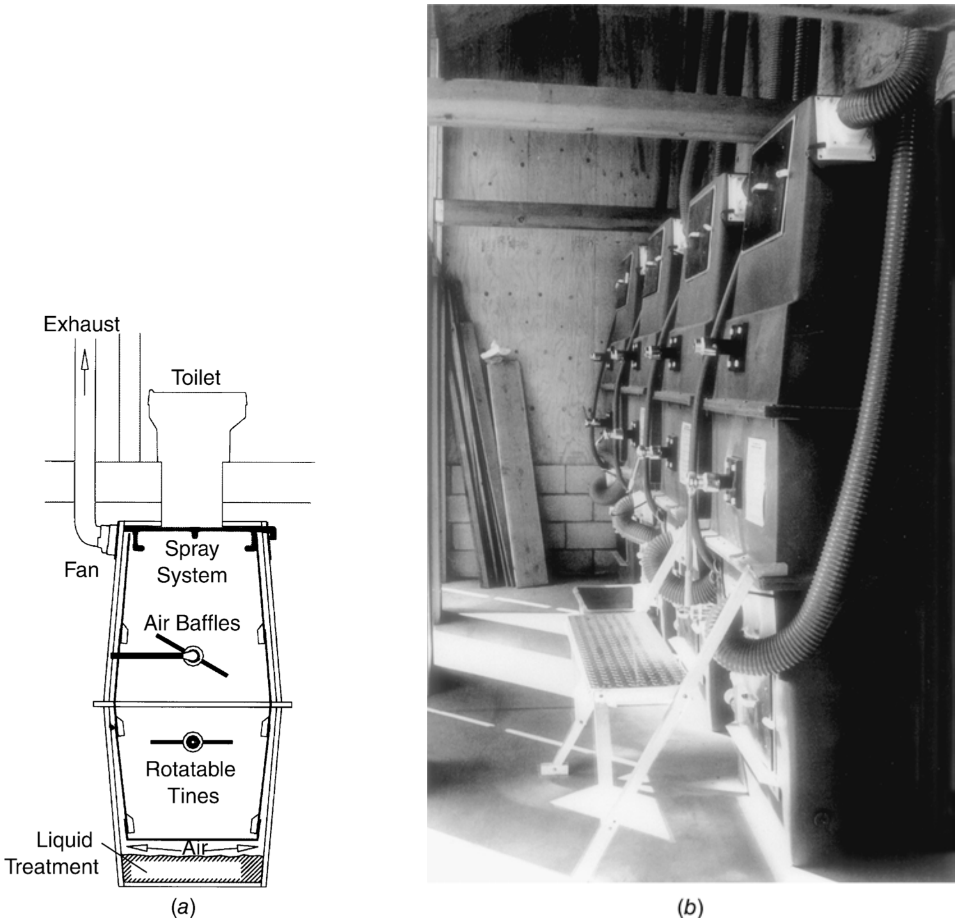


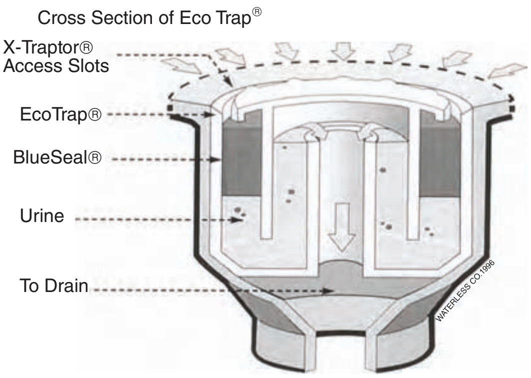
Fig. 20.5 *The Phoenix composting toilet's tank serves either two toilets, or one toilet and one food waste inlet. (a) Schematic section; rotatable tines mix waste and control the movement of compost to the access area for eventual removal. The fan exhausts air from the Phoenix tank to control odors. Passing behind the air baffles, air makes frequent contact with the compost pile, ensuring aerobic decomposition. After passing through the compost pile and receiving secondary treatment in the bottom of the Phoenix, liquid is periodically sprayed on top of the compost pile to keep the pile moist, and to introduce decomposing organisms to the fresh waste. Each tank is 39 in. (1000 mm) wide, 61 in. (1550 mm) long, and requires another 60 in. (1525 mm) in front for maintenance access; they are available in three heights: 55 in. (1400 mm), 73 in. (1850 mm), and 92 in. (2350 mm). Another 12 in. (300 mm) above the top of the tank is convenient for maintenance. (b) Four chambers with their rotatable tines serve the Vogelsang High Sierra Camp at Yosemite National Park, California. (Courtesy of Advanced Composting Systems, Whitefish, MT.)*

Fig. 20.6 *The Sun-Mar "Compact" composting toilet has a "Bio-drum"™ that is turned by a hand crank. The crank folds back into the body of the toilet after use. It also uses a 200-W electric heater to speed decomposition, a 25-W fan, and a 2-in. (50-mm) vent that attaches at the rear. The self-contained unit is designed for light residential use. (Courtesy of Sun-Mar Corporation, Tonawanda, NY.)*

20.2 PRINCIPLES OF DRAINAGE

Early in the history of indoor plumbing, waste drainage was a simple matter; a pipe containing wastewater led to a sewer (Fig. 20.8*a*). Before long, though, the noxious gases that were created by the anaerobic conditions in sewers became a threat to the health of those indoors. Thus, the *trap* was invented (Fig. 20.8*b*) to block the pipe so that gases could not pass. However, as moving water fills the pipe downstream from a trap, the mass of water acts as a plunger, creating higher pressures in front and negative pressures behind. The positive pressures might force sewer gas through the water in other traps; worse, the negative pressure could

(*a*)



(*b*)

Fig. 20.7 *Using no water, (a) the Waterless No-Flush™ urinal employs a special liquid to allow urine to pass through (b) while keeping sewer gas trapped in the waste pipe. (Courtesy of the Waterless Company LLC, Del Mar, CA.)*

suck (or siphon) the water from the trap, leaving it open to gas passage. The installation of *vents* provides a way to deal with these pressures so that the suction draws air down through the vents rather than water from the traps (Fig. 20.8*c*). A typical arrangement of fixtures, traps, and vents is shown in Fig. 20.9.

(a) Traps

The only separation between the unpleasant and dangerously unhealthy gases in sanitary drainage pipes and the air breathed by room occupants is the water caught in the fixture trap after each discharge from a fixture. Sufficient water must flow, especially in water closets, to keep this residual water clean. Traps are made of steel, cast iron, copper, plastic, or brass—except those in water closets and urinals, which are often made of vitreous china cast integrally with the fixture. The deeper the seal, the more resistance to siphonage, but the greater the fouling area; therefore, a minimum depth of 2 in. (50 mm) and a maximum depth of 4 in. (100 mm) are common standards. All traps should be self-cleaning, that is, capable of being completely flushed each time the trap operates so that no sediment will remain inside to decompose.

There are a few exceptions to the rule that each fixture should have its own trap. Common exceptions include two laundry trays and a kitchen sink connected to a single trap; not more than three laundry trays using one trap; and three lavatories on a single trap. In the case of the laundry trays and sink, the sink is equipped with the trap and set closest to the stack (see stack *s* in Fig. 20.9).

Traps are usually placed within 2 ft (610 mm) of the fixture and should be accessible for cleaning through a bottom opening that is otherwise closed by a plug. Overflow pipes from fixtures are connected to the inlet side of the trap. In long runs of horizontal pipe, so-called running traps are used only near drains in floors, areaways, or yards and should be provided with handhole cleanouts. "Island" sinks pose a special problem when the vent line cannot lead up from such an exposed location. The sink's waste line can be taken to a distant sump, which is then itself trapped and vented.

When fixtures are used very infrequently, the water in traps can evaporate into the air, breaking the seal of the trap. In contemplating the possible frequency of use, this fact should be kept in mind by the designer. Unoccupied residences (such as weekend or vacation homes) may experience sewer gas penetration through traps emptied by evaporation. Otherwise, evaporation to a dangerous degree rarely occurs, except in the case of floor drains. Used to carry away the water

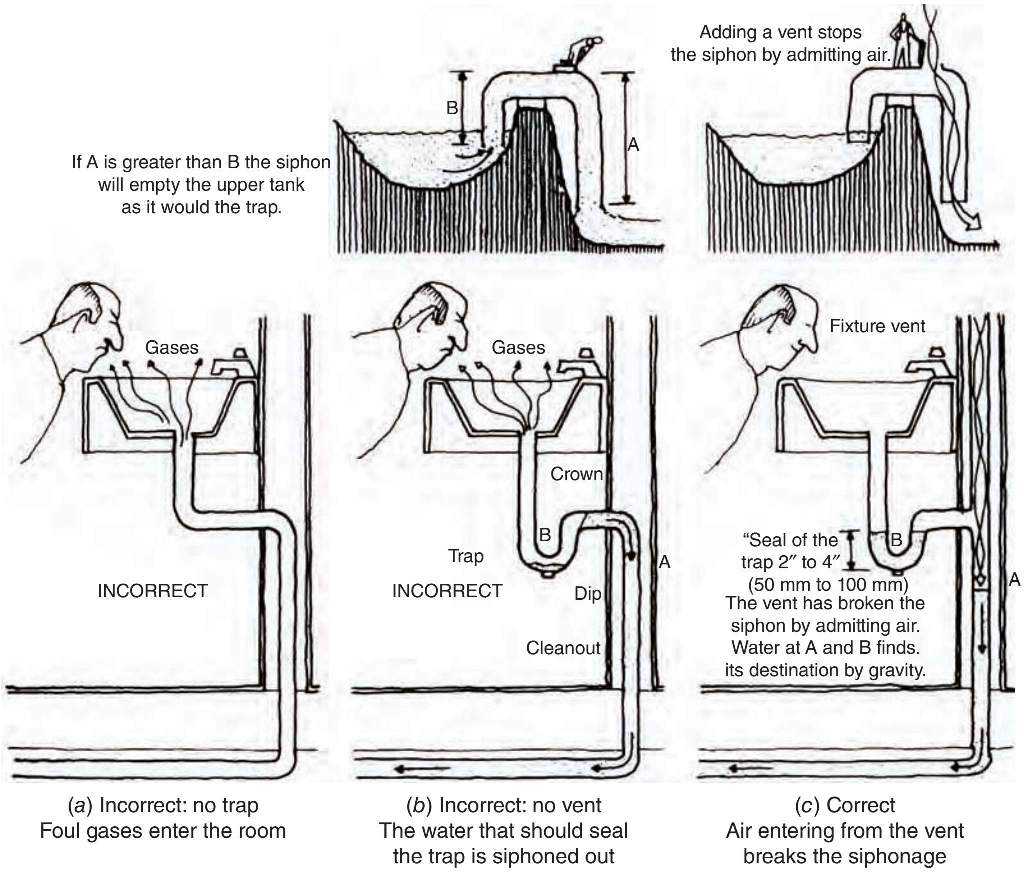


Fig. 20.8 *Function of a trap and one of the several functions of a vent (preventing siphonage).*

used in washing floors or drained from heating/cooling equipment, floor drains may often lose their water seal between their infrequent uses. Some authorities are reluctant to approve floor drains connected to a building sewer, requiring instead that they be separately connected to a dry well. In either case, the use of a special hose bibb, affording a source of water directly above the drain, is a wise precaution. It can easily be used to manually refill the trap of the drain. Other strategies include using a deep trap drain and/or providing a drip source of water to maintain the trap seal.

(b) Vents

To admit air and discharge gases, soil and waste stacks are extended through roofs, and a system of air vents, largely paralleling the drainage system, is provided. As in the case of drainage stacks, the ventilating stacks extend through the roof or vent through the drainage stack. The functions of venting are often misunderstood. It is true that one important purpose is to ventilate the system by allowing air from the fresh-air inlet (or from the sewer, if there is no house trap or fresh-air inlet) to rise through the system and carry away offensive gases. This provides some purification for the piping. However, several other purposes are served by the vent piping. The introduction of air near a fixture (and, in the case of circuit vents, at the branch soil line) breaks the possible siphonage of water out of a trap. Under other circumstances—namely, when drainage fluids descend to a fixture group through the soil stack—the foul gases, under pressure, could bubble through the trap seals of that

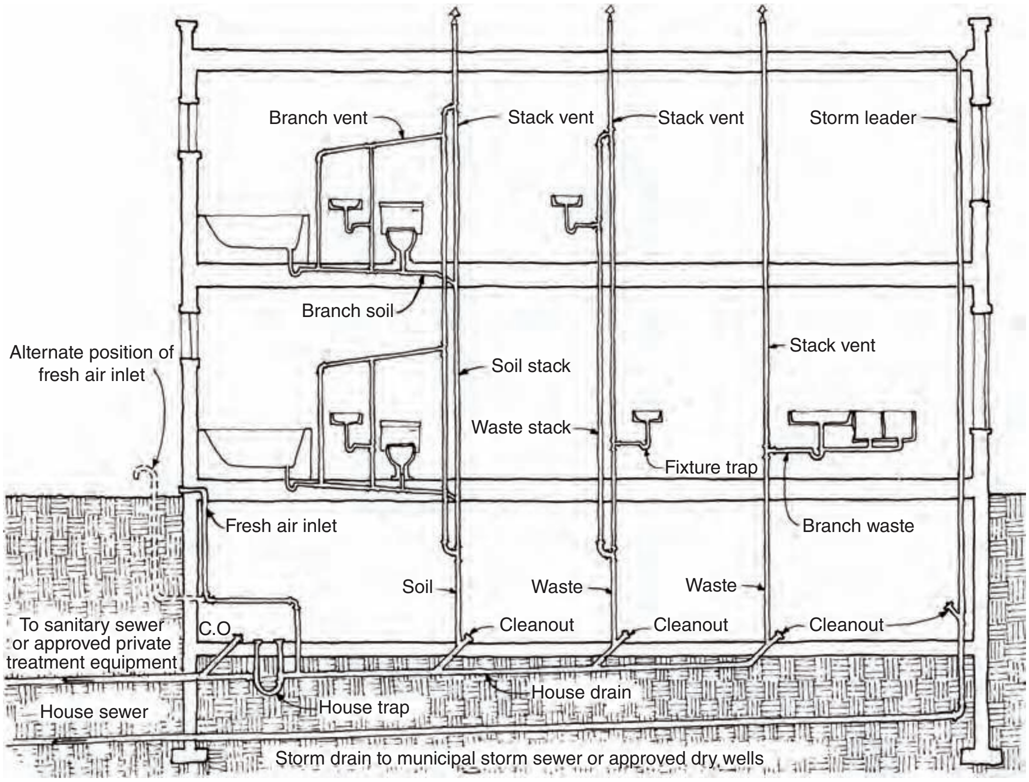


Fig. 20.9 *Typical sanitary drainage system, which separates storm water from sewage. This installation combines blackwater (from water closets) and graywater, although their separation would encourage graywater recycling. The house trap is optional under some plumbing codes and illegal under others (because sanitary sewers could be vented at street level through the fresh air inlet).*

group. The vent system provides a local escape for these gases. *Circuit venting* permits air and gases to pass in and out of the soil or waste branch, instead of at each fixture (as is the case of continuous venting in individual fixture venting); this can prevent the siphonage of trap seals or their penetration by gases (Fig. 20.10). Some codes may prohibit circuit venting.

(c) Air Gaps and Vacuum Breakers

Nearly every plumbing fixture is supplied with pure water at one point, and most discharge contaminated fluids at another. The proximity of sewage to potable water at most fixtures is inescapable; sewage could accidentally be siphoned into a pipe carrying potable water. Consider an improperly placed faucet whose outlet is below the rim of a fixture. If the fixture overflow is plugged and the fixture bowl full, the faucet can easily project into the foul drainage water. If, in this circumstance, the water piping is drained while the faucet is open, contaminated water could be drawn by suction into the water piping.

In water closets served by flushometers (flush valves), the water supply unavoidably enters the bowl below the rim. A vacuum breaker placed in the flushometer closes with water pressure but opens to admit air if there is suction in the water pipe. This prevents siphonage in much the same way that a vent prevents trap siphonage (Fig. 20.11). The use of vacuum breakers at dishwashers and clothes washers was diagrammed in Figure 19.52. These are especially important locations because, in both of these appliances, pumps force wastewater into a drain line.

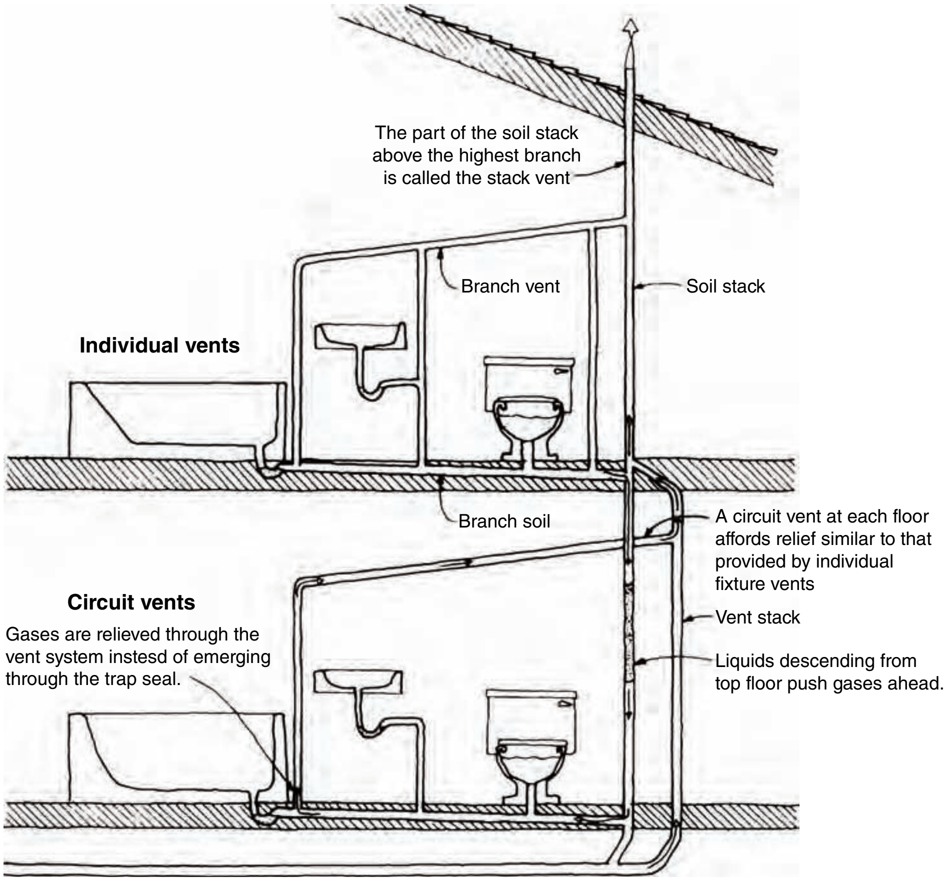


Fig. 20.10 *Sewer gas relief through vents. Gases that are pressurized, either via hydraulic action or by expansion due to putrefaction, have an escape path through the vent system—keeping said gases from entering the rooms. The upper floor shows individual vents (a vent at each fixture); the lower floor shows circuit vents, permitted by some codes, where one vent serves the entire branch.*

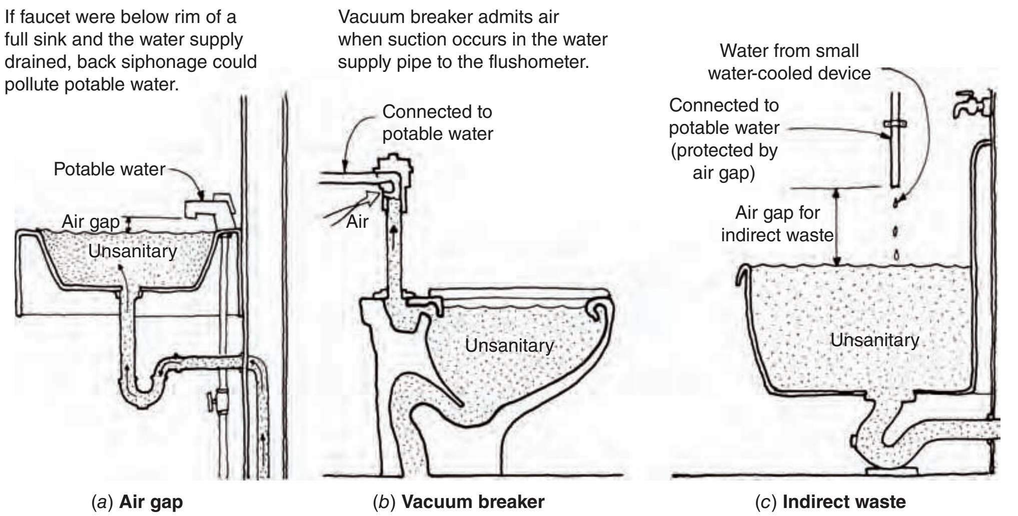


Fig. 20.11 *Backflow preventers. Unsanitary fluid wastes cannot be siphoned into the potable water piping in these three examples.*

20.3 PIPING, FITTINGS, AND ACCESSORIES

(a) Piping and Fittings

The materials used within buildings for soil and waste piping, and for venting, include cast iron, copper, acrylonitrile butadiene styrene (ABS) plastic, and polyvinyl chloride (PVC) type drainage, waste, and vent (DWV) pipe (Table 20.1, Fig. 20.12). Galvanized steel is sometimes chosen for vents and for tall stacks in high-rise structures. Sometimes, different materials are used in the same system. Where dissimilar metals are connected, dielectric unions are used to prevent corrosion due to electrolysis. Materials used underground for sewage disposal (depending upon local codes) include vitrified clay tile, cast iron, copper, asbestos-cement, ABS plastic, PVC type DWV, and concrete pipe.

Cast Iron. Used first in Germany around 1562 and appearing in the United States about 1813, cast iron supplanted the tubing and culverts of earlier eras that employed clay, lead, bronze, and wood. Cast iron was thus the earliest of the modern materials used for piping. Its durability and resistance to corrosion make it appropriate for a wide range of uses, from small residential work to the stacks and branches of tall buildings.

Typical fittings for sanitary drainage appear in Figs. 20.12 and 20.13. In sanitary flow systems that are composed of *any* material, changes in direction must be made with easy bends. To prevent clogging or fouling by the solid materials flowing in the piping, right-angle connections are not used. Thus, for sanitary drainage systems, the available options in Fig. 20.13 would be the one-eighth bend connected to a 45° Y, or the one-quarter bend long sweep. The 90° T, in the position shown, would be used *only* in a vent system.

The three cast-iron soil pipe joints shown in Fig. 20.14 represent semi-rigid, watertight, and gastight connections of two or more pieces of pipe or fittings in a sanitary system. Types *b* and *c* provide a quieter plumbing system and slightly more flexible joints than type *a*. See Fig. 20.15 for cast-iron soil pipe and fittings in bathroom groups.

Copper Tube and Fittings for DWV. There are several tube classifications for the copper products used in plumbing systems: types K, L, and M are for water supply systems, and type DWV is for drainage, waste, and vent installations. Connections between copper tubing and its couplings or fittings involve a sliding fit between components (see Fig. 20.12*b*). Bridging the mating surfaces is a cylindrical capillary space filled with solder. The process of making the joint is a simple one, utilizing a flux, heat, and solder. Properly made, the joint will be airtight and capable of withstanding high pressure (although such pressure is not normal in waste lines). To undo the joint for repair or renovation, one simply reheats it until the solder melts. Like cast iron, copper has a history of use in ancient installations. Updated and highly developed in recent decades, it is now in widespread use.

TABLE 20.1 Materials for Waste Piping

		Underground	
Material	**Aboveground DWV**	**Building Drainage and Vent**	**Building Sewer**
ABS (acrylonitrile butadiene styrene)	✓	✓	✓
Asbestos-cement		✓	✓
Brass	✓		
Cast iron	✓	✓	✓
Concrete			✓
Copper (type)	✓ (K, L, M, or DWV)	✓ (K or L)	✓ (K or L)
Galvanized steel	✓		
Glass	✓		
Polyolefin	✓	✓	
PVC (polyvinyl chloride) type DWV	✓	✓	✓
Vitrified clay			✓

Source: Reprinted from the 2012 *International Plumbing Code*, www.iccsafe.org

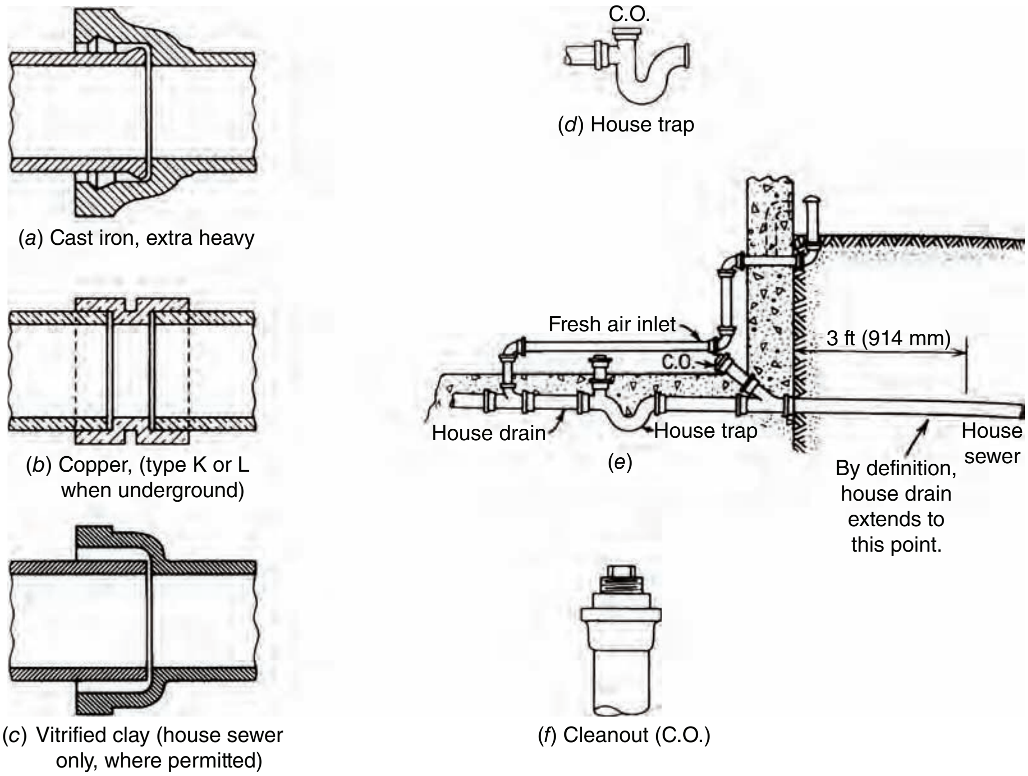


Fig. 20.12 *Piping and fittings. (a) Connection of cast-iron piping. (b) Coupling to connect copper tubing. (c) Connection of vitrified clay piping. (d) Detail of house trap fitting. (e) House drain, house trap with cleanouts and vent (fresh air inlet), and house sewer. (f) Cleanout showing removable threaded plug. For large buildings, the terms* building drain, building sewer, *and so on, supplant the terms* house drain, house sewer, etc. *Local codes differ on inclusion or omission of the house trap.* Note: *plastic pipe connections are similar to that in (b).*

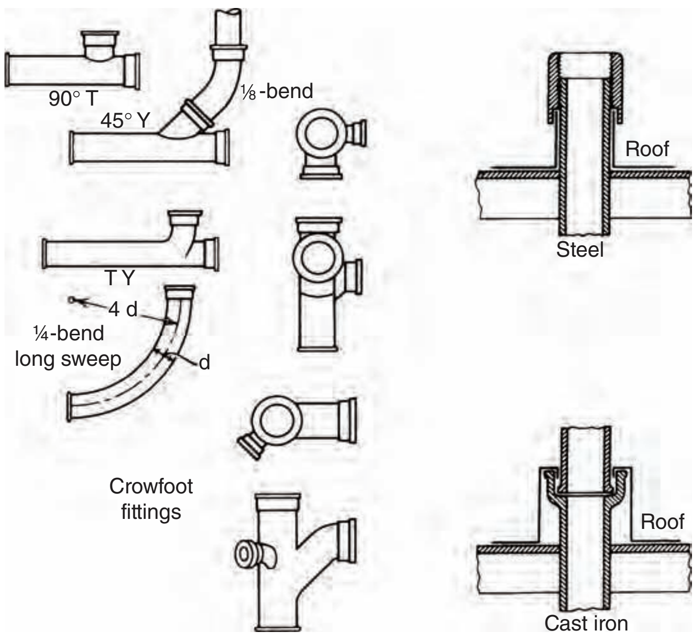


Fig. 20.13 *Principal types of cast-iron fittings and method of flashing at roofs for steel and cast iron.*

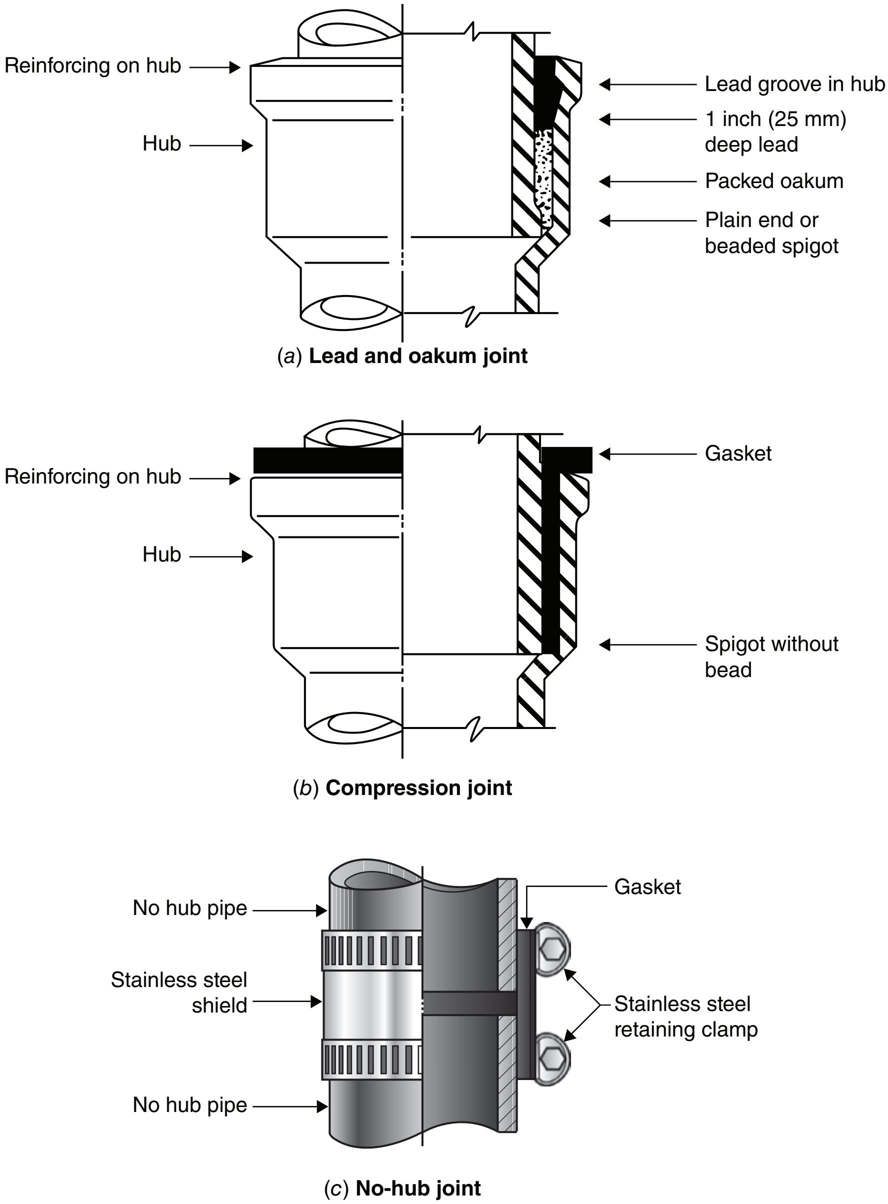
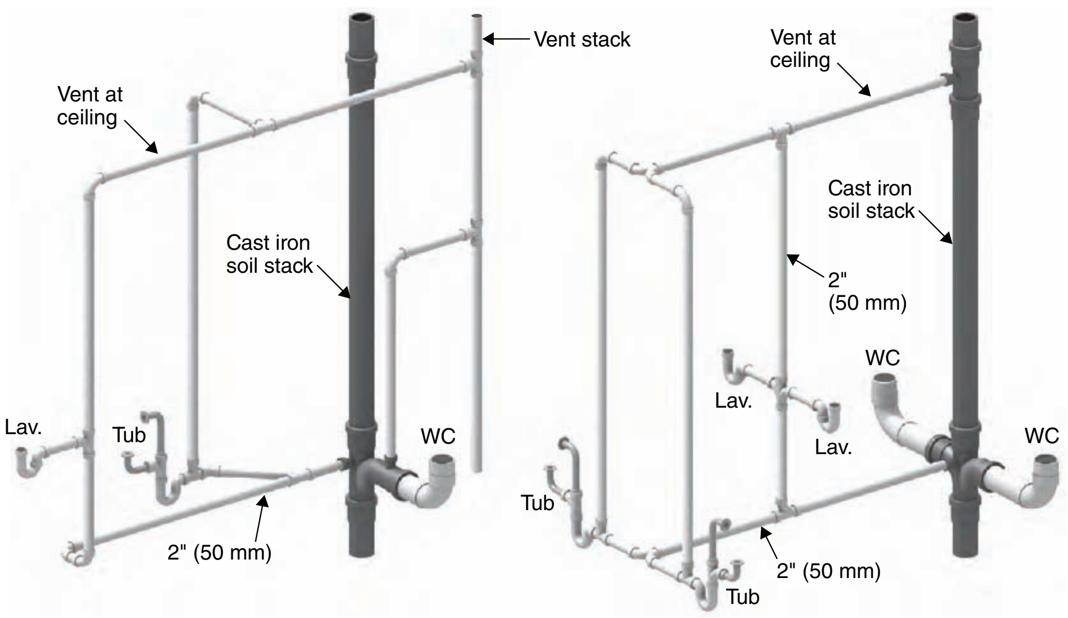


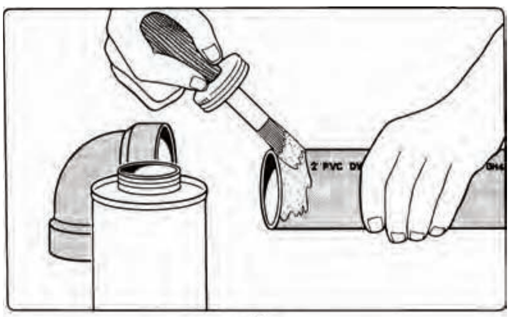
Fig. 20.14 *Various joints used to connect cast-iron soil pipe and fittings. (Courtesy of the Cast Iron Soil Pipe Institute.)*

Plastic Materials for DWV. Along with copper and cast iron, plastics are suitable for sanitary drainage systems. Table 20.1 lists the plastics suitable for drainage, waste, and vent, as well as for building drains and sewers. Acrylonitrile butadiene styrene (ABS) is identified and further described by the labeling shown in Fig. 20.16. One of several steps used in making a “solvent-weld” connection is seen in Fig. 20.16, as is a method of support used in wood frame construction. Figure 20.17 shows assembled bathroom piping in place. One advantage of plastic piping is its relatively light weight, allowing some preassembly in a location with conditions better than might be available at the final installation location—the assembly then being carried to its place of installation.

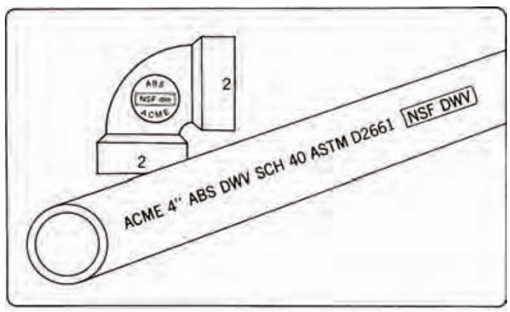


(*a*) (*b*)

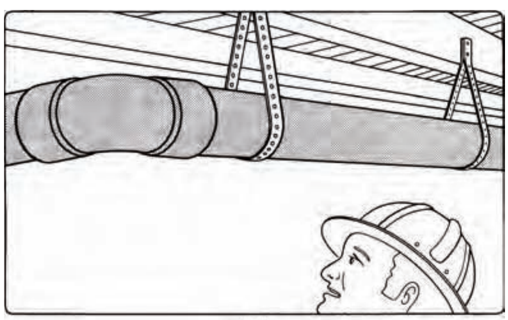
Fig. 20.15 *Two typical piping arrangements for a water closet, lavatory, and tub. (a) For a multistory installation with each fixture vented; (b) for a single-story, back-to-back installation. (Courtesy of the Cast Iron Soil Pipe Institute.)*



(*a*)



(*c*)



(*b*)

Fig. 20.16 *Details of the use of plastic pipe. (a) One of the steps in making a solvent weld of a plastic pipe to a plastic fitting. (b) In wood frame construction, plastic pipe assemblies can be supported by metal straps nailed to wood joists. The supports should be more closely spaced than those for metal piping because of plastic's increased flexibility. (c) Typical identification symbols on plastic pipe: ACME—the name of the manufacturer; 4-in. (102-mm)—the diameter of the pipe; ABS—acrylonitrile butadiene styrene, the material; DWV—suitable for drainage, waste, and vent; SCH 40—Schedule 40, this identifies the wall thickness of the pipe; ASTM D2661—the applicable American Society for Testing and Materials standard; NSF DWV—tested by the National Sanitation Foundation Testing Laboratory, the pipe meets or exceeds the current standards for sanitary service. (Courtesy of the Plastic Pipe Institute.)*

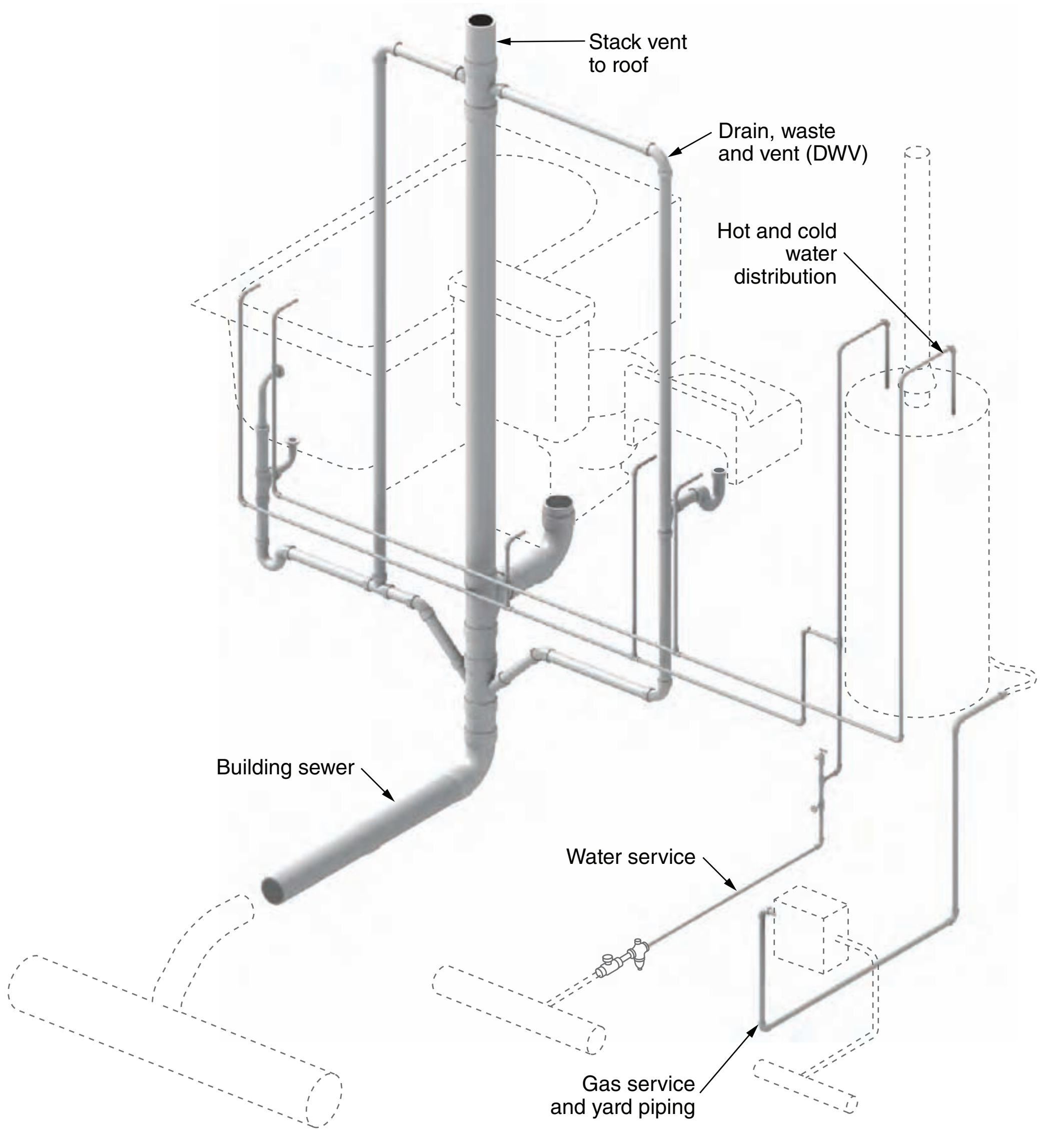


Fig. 20.17 *Plastic piping (solid lines) for water service, gas service, hot and cold water supply, and for drainage, waste, and vent. Gas service below grade can be PE, PB, or PVC. (Courtesy of the Plastic Pipe Institute.)*

(b) Accessories

Among the many special devices that can form part of a plumbing system are floor drains, backwater valves, ejectors, and interceptors.

Floor Drains. When floors in buildings must be washed down after operations such as food preparation and cooking, floor drains are usually necessary. Figure 20.18 shows a typical floor drain. Because these drains are often connected to sanitary drainage systems (rather than dry wells) and, in long periods of disuse, might lose their trap seals by evaporation, special precautions are necessary to preserve the trap seal and avoid odors and unsanitary conditions in the room.

Backwater Valves. These devices (Fig. 20.19) are sometimes used when plumbing fixtures are

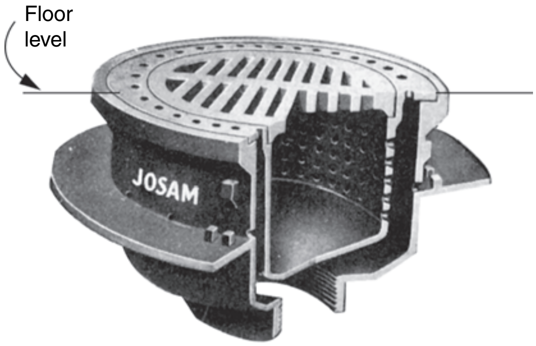


Fig. 20.18 Floor drain. (Courtesy of the Josam Manufacturing Company.)

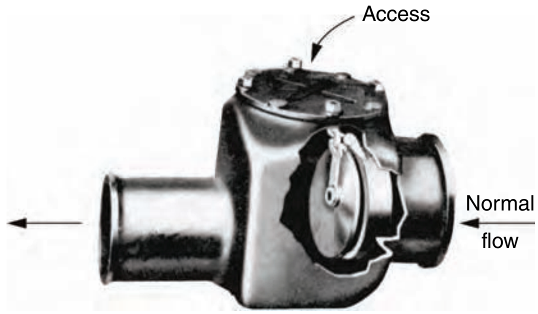


Fig. 20.19 Backwater valve, with access to facilitate unclogging and cleaning.

installed at low elevations, such as in basements, or in other locations that are near the level of the sewer. They cannot be used to protect the entire plumbing system and should be used only when necessary. They must be accessible for maintenance. An alternative to the use of backwater valves is the sewage sump.

Sewage Sumps and Ejectors. Whenever subsoil drainage, fixtures, or other equipment are situated below the level of public sewers, a sump pit or receptacle must be installed. The drainage from the low fixtures may flow into this pit by gravity, and from it the contents are then lifted (ejected) up into the building sewer. Sewer ejectors may be motor-driven centrifugal pumps (Fig. 20.20), or they may be operated by compressed air. The latter have no revolving parts within the receptacle. An air compressor is started when a float within the sump

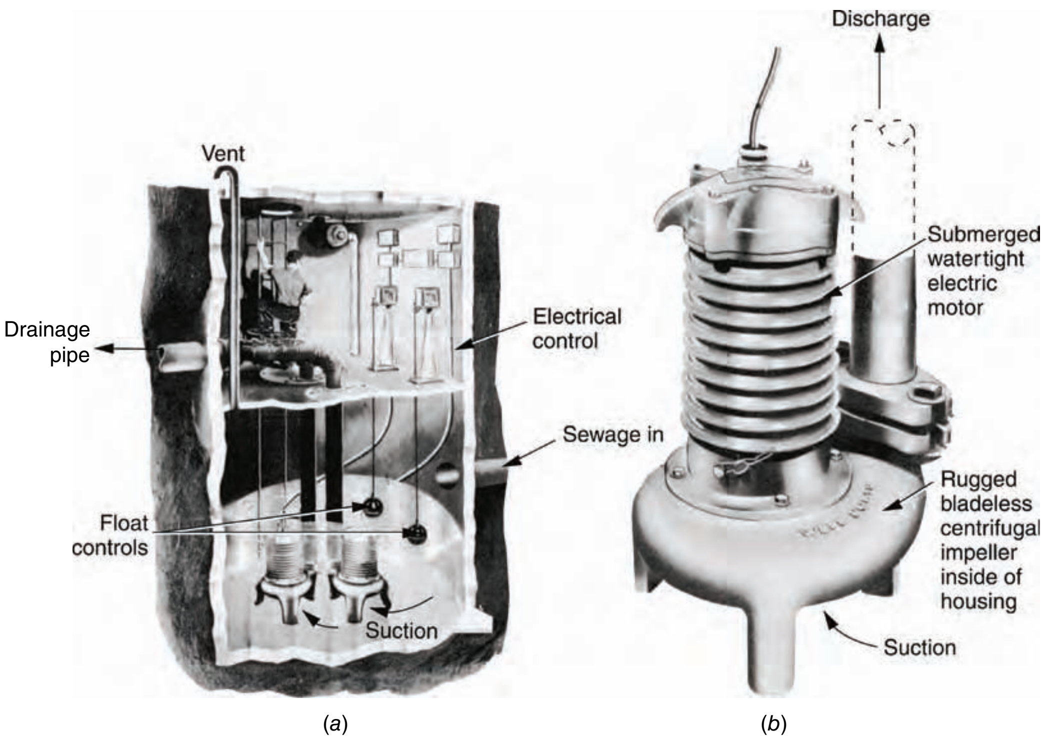


Fig. 20.20 Sump (a) and ejector pump (b). A submersible-type centrifugal pump for raising sewage to a higher level. Shown here for an outdoor subgrade sump installation, it may be used in basement applications within buildings. Venting must be carried to the roof. (Courtesy of the Weil Pump Company.)

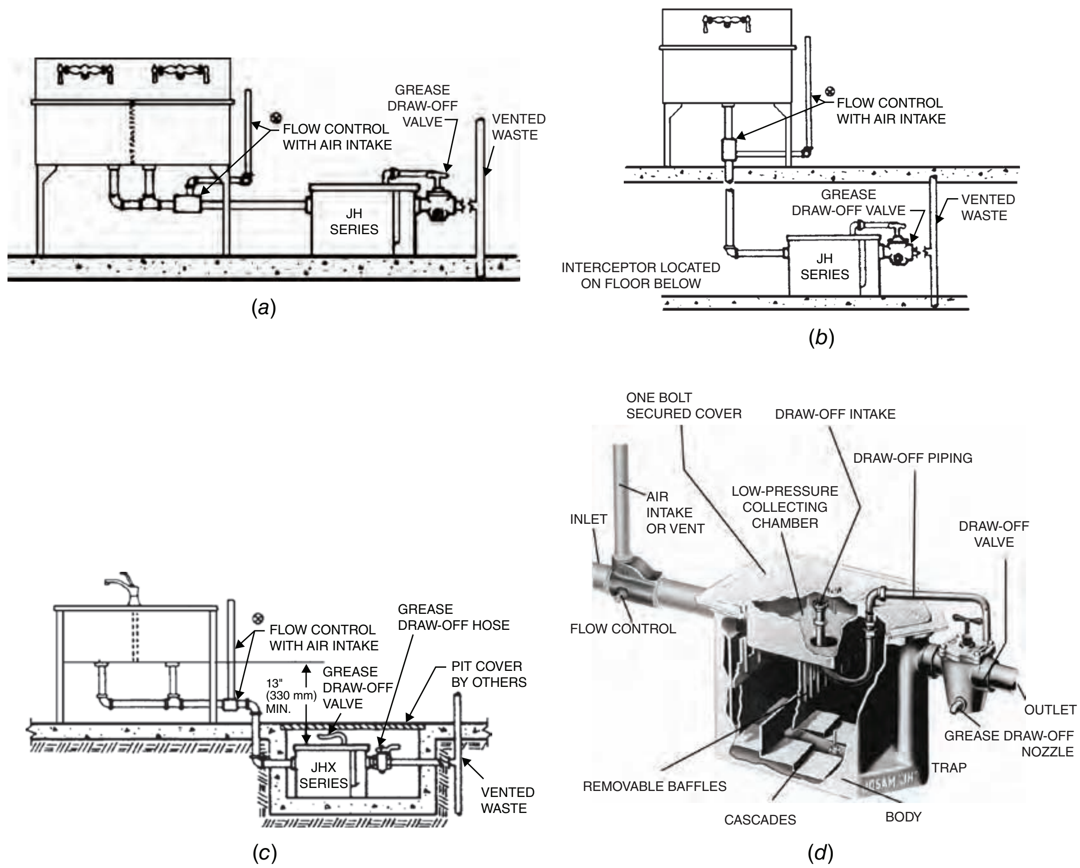


Fig. 20.21 *One type of institutional interceptor, a grease trap. Choice of three locations—adjacent to the sink (a), on the floor below (b), or in a pit (c). Periodic cleaning is both necessary and unpleasant; easy access is helpful. (d) Cutaway view with identification of component parts. (Courtesy of the Josam Manufacturing Company.)*

reaches a certain level, and air at a pressure greater than 0.433 psi for each foot (10 kPa for each meter) of lift is delivered into the space above the liquid. The air pressure closes the inlet and opens the outlet check valves, expelling the contents of the sump and elevating it to the sewer.

Interceptors. Sanitary drainage installations ultimately discharge their waste matter into private or public sewage treatment plants that attempt to digest or cope with anything that may come through the pipes. Because it is impossible to control what will be discarded into the plumbing drains, trouble can occasionally be expected. The problem can be reduced somewhat by devices known as *interceptors*, which catch foreign matter before it travels too far into the system.

Interceptors require periodic servicing. Interceptors for as many as 25 different kinds of extraneous material are listed by manufacturers. They include devices to catch hair, grease, plaster, lubricating oil, glass grindings, or material from many industrial processes. One of the few interceptors that is sometimes used in homes, but more often in institutional kitchens, is the grease interceptor, or *grease trap*. As the waste is passed from a kitchen sink through the circuitous path within the grease interceptor, the grease floats to the top, where it is trapped between baffles, while the more fluid wastes pass through at a lower level (Fig. 20.21). If not so intercepted, grease congeals within piping and thus physically retards the sewage collection process.

Cleanouts. Clogging of sanitary drainage piping systems is very possible—if not likely. From all plumbing fixtures to the end of the disposal process, all parts of a sanitary piping system should be accessible through cleanouts (Fig. 20.12) and/or other points of access to relieve clogging that will often occur in the piping (as well as in the septic tank or public disposal plant).

20.4 DESIGN OF RESIDENTIAL WASTE PIPING

In residential work, the piping assemblies may often look like a "flag," where the mast is the soil stack, the horizontal top of the flag is the branch vent, the bottom is the soil or waste branch, and the outer edge is the vertical pipe of the last fixture. In wood or steel frame construction, the flag usually fits into a 6-in. (150-mm) partition. Fixture branches project from the surface of the flag. There is considerable advantage in back-to-back layouts for baths and kitchens; this allows the piping assembly to pick up the drainage from fixtures on both sides of the piping. When all the fixtures are on nearly the same level, it is unnecessary to have a separate vent stack next to the soil stack, as is often the case in multistory construction. Generally in one-story construction, the upper part of the soil stack is extended to form a vent called a *stack vent*, to which the branch vents connect. A separate major vertical vent is called a *vent stack*.

The task of fitting two generally parallel plumbing "distribution trees" (supply and waste) into available horizontal and vertical chases can be difficult. This is especially true of the waste system, which has larger pipes, because it is not under pressure and must carry solids as well as liquids. To compound the problem, because of gravity flow requirements, these larger pipes must slope continuously downward, from fixtures to the sewer. In residences, the best available "vertical chase" is sometimes nothing more than an extra-thick wall, increasing the difficulty of coordination.

In residential applications (and other relatively small buildings), certain fairly standard minimum sizes (such as a 4-in. [102-mm] soil stack and building drain) are usually adequate. Horizontal fixture branches from *individual* fixtures should be the same size as the fixture trap. Horizontal fixture branches from *groups* of fixtures are sized by the drainage fixture units of the group. For individual fixture vents, the vent size is usually the same as the size of the fixture's horizontal branch. Under many codes, vertical vents that penetrate the roof must increase to a 4-in. (102-mm) size to prevent blocking by icing in freezing weather.

Tables 20.2 through 20.5 list minimum pipe sizes to carry waste and serve for venting.

EXAMPLE 20.1 Design, lay out, and size the piping for the sanitary drainage system for the house shown in Fig. 20.22. Use I-P units.

SOLUTION

The first step is to identify the locations where hot and cold water is needed at fixtures, and where soil or waste drains must be provided. Figure 20.23*a* illustrates how this is done. A plan layout for the drains in both levels follows (Fig. 20.23*b*).

Next comes the plumbing section (Fig. 20.24). The local administrative authority usually requires this to be submitted for approval. Pipe sizes are determined from Tables 20.2 through 20.5. Drainage fixture units (dfu) for this system are summarized in Table 20.6 from data given in Table 20.2.

Although Table 20.3 permits a 3-in. (76-mm) branch for up to 20 dfu, it is common practice to use a 4-in. (102-mm) branch for every water closet (or every group of water closets totaling 20 dfu or less). Because Table 20.3 allows 160 dfu for a 4-in. (102-mm) branch, this size is acceptable for any branch to which a water closet is connected. This size is also more than adequate for the stack in this example.

A water closet must have a 2-in. (51-mm) vent. Table 20.4 shows that a 2-in. (51-mm) vent, for developed vent lengths not exceeding 150 ft (45.7 m), will serve 20 dfu. This size is acceptable for all branch vents in this example.

The house drain should not be less than 4 in. (102 mm). From Table 20.5, at a ¼-in. fall per foot (2.1% slope), a 4-in. (102-mm) house drain will carry 216 dfu, which is more than adequate for the 26-dfu system. ■

There are prefabricated bathrooms in which a manufacturer assembles the piping for preselected fixtures. Going further, there are a few examples of entirely one-piece bathrooms, which incorporate the maintenance advantage of having no seams between fixtures, walls, and floors. This, of course, makes fixture replacement expensive and difficult, and tends to put the burden of access to plumbing on adjacent rooms.

For the more ordinary bathroom, the two maintenance questions of greatest concern are: (1) How easy is cleaning around and within the fixture? and (2) How accessible are those parts of the fixture most likely to need repair or replacement?

TABLE 20.2 Drainage Fixture Units (dfu)

PART A. BY TYPE OF FIXTURE

Fixture(s)	Drainage Fixture Units (dfu)	Minimum Trap Size in.	Minimum Trap Size mm[a]
Automatic clothes washers: Commercial[b]	3	2	51
Residential	2	2	51
Bathroom group: Water closet (1.6 gpf [6 Lpf]), lavatory, and bathtub or shower; with or without a bidet and emergency floor drain	5	—	—
Bathroom group: Water closet (>1.6 gpf [6 Lpf]), lavatory, and bathtub or shower; with or without a bidet and emergency floor drain	6	—	—
Bathtub[c] (with or without overhead shower or whirlpool)	2	1½	38
Bidet	1	1¼	32
Combination sink and tray	2	1½	38
Dental lavatory	1	1¼	32
Dental unit or cuspidor	1	1¼	32
Dishwashing machine[d], domestic	2	1½	38
Drinking fountain	0.5	1¼	32
Emergency floor drain	0	2	51
Floor drains	2	2	51
Kitchen sink, domestic	2	1½	38
Kitchen sink, domestic, with food waste grinder and/or dishwasher	2	1½	38
Laundry tray (1 or 2 compartments)	2	1½	38
Lavatory	1	1¼	32
Shower	2	1½	38
Service sink	2	1½	38
Sink	2	1½	38
Urinal	4	[e]	
Urinal, 1 gal (3.8 L) per flush or less	2[f]	[e]	
Urinal, nonwater supplied	0.5	[e]	
Wash sink (circular or multiple) each set of faucets	2	1½	38
Water closet, flushometer tank, public or private	4[f]	[e]	
Water closet, private (1.6 gpf [6 Lpf])	3[f]	[e]	
Water closet, private (>1.6 gpf [6 Lpf])	4[f]	[e]	
Water closet, public (1.6 gpf [6 Lpf]),	4[f]	[e]	
Water closet, public (flushing >1.6 gpf [6 Lpf])	6[f]	[e]	

PART B. BY SIZE OF TRAP

Fixture Drain or Trap Size in.	Fixture Drain or Trap Size mm[a]	Drainage Fixture Unit (dfu) Value
1¼	32	1
1½	38	2
2	51	3
2½	64	4
3	76	5
4	102	6

Source: Reprinted from the 2012 *International Plumbing Code*, © International Code Council (ICC), Washington, D.C. All rights reserved. www.iccsafe.org

[a]SI conversions provided by the authors (not part of original source).

[b]For traps larger than 3 in. (76 mm), see Part B of this table.

[c]A showerhead over a bathtub or whirlpool bathtub attachments do not increase the dfu value.

[d]For ratings of fixtures not listed or for intermittent flows, see the current edition of the *International Plumbing Code*.

[e]Trap size shall be consistent with fixture outlet size.

[f]For computing loads on building drains and sewers, water closets or urinals shall not be rated at a lower dfu unless the lower values are confirmed by testing.

Ease of cleaning is often determined more by the space around the fixture than by the design of the fixture itself. This is particularly true of toilets, where a generous amount of open floor on either side makes maintenance easy and therefore likely to be more frequent. Access to fixture parts may be more difficult. An access panel in the wall of the room behind the fixtures is often provided, encouraging speedy repair and replacement for components at tubs, showers, and lavatories. Ideally,

TABLE 20.3 Horizontal Fixture Branches and Stacks[a]

Diameter of Pipe			*Maximum Total Number of dfu Allowable*		
			Stacks[b]		
in.	**mm[c]**	**Horizontal Branch**	**One Branch Interval**	**Three Branch Intervals or Less**	**Greater than Three Branch Intervals**
1½	38	3	2	4	8
2	51	6	6	10	24
2½	64	12	9	20	42
3	76	20	20	48	72
4	102	160	90	240	500
5	127	360	200	540	1100
6	152	620	350	960	1900
8	203	1400	600	2200	3600
10	254	2500	1000	3800	5600
12	305	3900	1500	6000	8400
15	381	7000	[d]	[d]	[d]

Source: Reprinted from the 2012 *International Plumbing Code*, © International Code Council (ICC), Washington, D.C. All rights reserved. www.iccsafe.org

[a]Does not include branches of the building drain; see Table 20.5.

[b]Stacks shall be sized based on the total accumulated connected load at each story or branch interval. As the total accumulated connected load decreases, stacks may be reduced in size. Stack diameters shall not be reduced to less than one-half the diameter of the largest stack size required.

[c]SI conversions provided by the authors (not part of original source).

[d]Sizing load based upon design criteria.

accessibility to all plumbing lines—whether via access panels in walls, trenches in concrete floors, exposed basement ceilings, or adequately deep crawl spaces—should be provided. Most bathrooms are likely to undergo thorough remodeling, including fixture replacement, as styles change and water/energy conservation becomes more important.

20.5 DESIGN OF LARGER-BUILDING WASTE PIPING

(a) Basic Planning

Multistory construction, especially in office buildings, is often designed to be flexible and free of random partitions that would interfere with the periodic renovation and reorganization of interior spaces. Building "cores" contain elevators, stairs, and shafts for plumbing, mechanical, and electrical equipment. Cores are often placed in the central section of the building, freeing the surrounding areas for access to daylight. A hole in the floor for each pipe is often chosen in preference to a slot or shaft. This method usually interferes less with the floor construction (Fig. 20.25).

Offices often need a single lavatory or a complete toilet room for executives at locations away from the central core of the building. The greater the horizontal distance from the core, the more vertical clearance that will be needed to allow the drain to slope. When such vertical clearance becomes difficult, "wet" columns with a full complement of plumbing pipes offer a solution. If the pipes are to accompany a column in a steel building, structural coordination must be sought early in the planning (Fig. 20.26).

In some installations, the branch soil and waste piping perforates a floor and crosses below the slab to join the stack. Tubing has been developed, however, that sits above the structural slab, obviating the need for hung ceilings below (Fig. 20.27). A lightweight concrete fill is cast to cover the tubing, raising the floor by 5 or 6 in. (125 or 150 mm), creating a raised floor in the toilet room—along with associated access problems. Given this, the higher floor level is usually carried throughout the entire story, forming a convenient space into which the electrical conduit

TABLE 20.4 Size and Developed Length of Stack Vents and Vent Stacks

Diameter of Soil or Waste Stack in. (mm)[b]	Total Fixture Units Being Vented (dfu)	*Maximum Developed Length[a] of Vent, Feet (m)[b]*									
		Diameter of Vent, In. (mm)[b]									
		1¼ (32)	1½ (38)	2 (51)	2½ (64)	3 (76)	4 (102)	5 (127)	6 (152)	8 (203)	10 (254)
1¼ *(32)*	2	30 (9.1)									
1½ (38)	8	50 (15.2)	150 (45.7)								
1½ (38)	10	30 (9.1)	100 30.5								
2 (51)	12	30 (9.1)	75 (22.9)	200 (61.0)							
2 (51)	20	26 (7.9)	50 (15.2)	150 (45.7)							
21⁄2 (64)	42		30 (9.1)	100 (30.5)	300 (91.0)						
3 (76)	10		42 (12.8)	150 (45.7)	360 (109.7)	1040 (317)					
3 (76)	21		32 (9.8)	110 (33.5)	270 (82.3)	810 (246.9)					
3 (76)	53		27 (8.2)	94 (28.7)	230 (70.1)	680 (207.3)					
3 (76)	102		25 (7.6)	86 (26.6)	210 (64.0)	620 (189.0)					
4 (102)	43		25 (7.6)	35 (10.7)	85 (25.9)	250 (76.2)	980 (298.7)				
4 (102)	140		25 (7.6)	27 (8.2)	65 (19.8)	200 (61.0)	750 (228.6)				
4 (102)	320			23 (7.0)	55 (16.8)	170 (51.8)	640 (195.0)				
4 (102)	540			21 (6.4)	50 (15.2)	150 (45.7)	580 (176.8)				
5 (127)	190				28 (8.5)	82 (25.0)	320 (97.5)	990 (301.8)			
5 (127)	490				21 (6.4)	63 (19.2)	250 (76.2)	760 (231.6)			
5 (127)	940				18 (5.5)	53 (16.2)	210 (64.0)	670 (204.2)			
5 (127)	1400				16 (4.9)	49 (14.9)	190 (57.9)	590 (179.8)			
6 (152)	500					33 (10.1)	130 (39.6)	400 (121.9)	1000 (304.8)		
6 (152)	1100					26 (7.9)	100 (30.5)	310 (94.5)	780 (237.7)		
6 (152)	2000					22 (6.7)	84 (25.6)	260 (79.2)	660 (201.2)		
6 (152)	2900					20 (6.1)	77 (23.5)	240 (73.2)	600 (182.9)		
8 (203)	1800						31 (9.4)	95 (29.0)	240 (73.2)	940 (286.5)	
8 (203)	3400						24 (7.3)	73 (22.3)	190 (57.9)	729 (222.4)	
8 (203)	5600						20 (6.1)	62 (18.9)	160 (48.8)	610 (185.9)	
8 (203)	7600						18 (5.5)	56 (17.1)	140 (42.7)	560 (170.7)	
10 (254)	4000							31 (9.4)	78 (23.8)	310 (94.5)	960 292.6
10 (254)	7200							24 (7.3)	60 (18.3)	240 (73.2)	740 225.6
10 (254)	11,000							20 (6.1)	51 (15.5)	200 (61.0)	630 192.0
10 (254)	15,000							18 (5.5)	46 (14.0)	180 (54.9)	571 (174.2)

Source: Reprinted from the 2012 *International Plumbing Code*, www.iccsafe.org

[a]The developed length is measured from the vent connection to the open air.

[b]SI conversions provided by the authors of this book (not part of original source).

TABLE 20.5 Building Drains and Sewers

Diameter of Pipe		*Maximum Number of dfu Connected to Any Portion of the Building Drain or Building Sewer, Including Branches of the Building Drain*[a] *Fall, in. per ft (% slope)*			
(in.)	**(mm)**[b]	**1/16 (0.5%)**	**1/8 (1.04%)**	**1/4 (2.1%)**	**1/2 (4.2%)**
2	51			21	26
2½	64			24	31
3	76		36	42	50
4	102		180	216	250
5	127		390	480	575
6	152		700	840	1000
8	203	1400	1600	1920	2300
10	254	2500	2900	3500	4200
12	305	3900	4600	5600	6700
15	381	7000	8300	10,000	12,000

Source: Reprinted from the 2012 *International Plumbing Code*, © International Code Council (ICC), Washington, D.C. All rights reserved. www.iccsafe.org

[a]The minimum size of any building drain serving a water closet shall be 3 in. (76 mm).

[b]SI conversions provided by the authors of this book (not part of original source).

can be placed at a time later than would have been required if it were to be placed in the structural slab. Such raised floors are becoming more common, along with the HVAC strategy of underfloor air distribution.

(b) Roughing-In

This is the process of getting all pipes installed, capped, and pressure-tested before the fixtures are installed. An example of roughing-in for an office building is shown in Fig. 20.27. The roughing-in of supply and waste piping for school lavatories is shown in Fig. 20.28.

Institutions such as schools have extensive requirements for durability and ease of maintenance. The fixtures are made of such wear-resistant materials as stainless steel, chrome-plated cast brass, precast stone or terrazzo, or high-impact fiberglass. The fixture controls are designed to withstand heavy use—or misuse—and the fixtures are securely tied into the structure with concealed mounting hardware designed to resist extraordinary forces. (Some schools even move the lavatories into the hallway for better visual control of at least a part of the restroom facilities.)

In prisons, extreme measures are taken to prevent plumbing fixtures from becoming damaged, or being used as weapons. Heavy-gauge stainless steel fixtures with nonremovable fittings are provided, at very high cost, for both the fixture and its tamper-proof installation.

EXAMPLE 20.2 Select drainage and vent piping sizes for the plumbing in an office building—for which the fixtures are shown in Fig. 20.29.

SOLUTION

Selected dfu values from Table 20.2 are applied to each section of the piping and totaled for each branch and stack, as well as for the building drain and the building sewer. Individual fixture branches should not be less than the size indicated in Table 20.3 for the minimum size of trap for each fixture. An example of a fixture-unit summary, and sample sizes of individual branches that connect into a typical branch of the men's toilet group on any floor, are shown in the following table.

Features	Units per Fixture	Total Fixture Units	Diameter, Fixture Branch in.	mm
1 service sink (2-in. [51-mm] trap)	3	3	3	76
3 lavatories	1	3	3	76
3 urinals, washout	4	12	2	51
3 water closets, valve operated	6	18	4	102
Total fixture units, men's toilet branch		**36**		

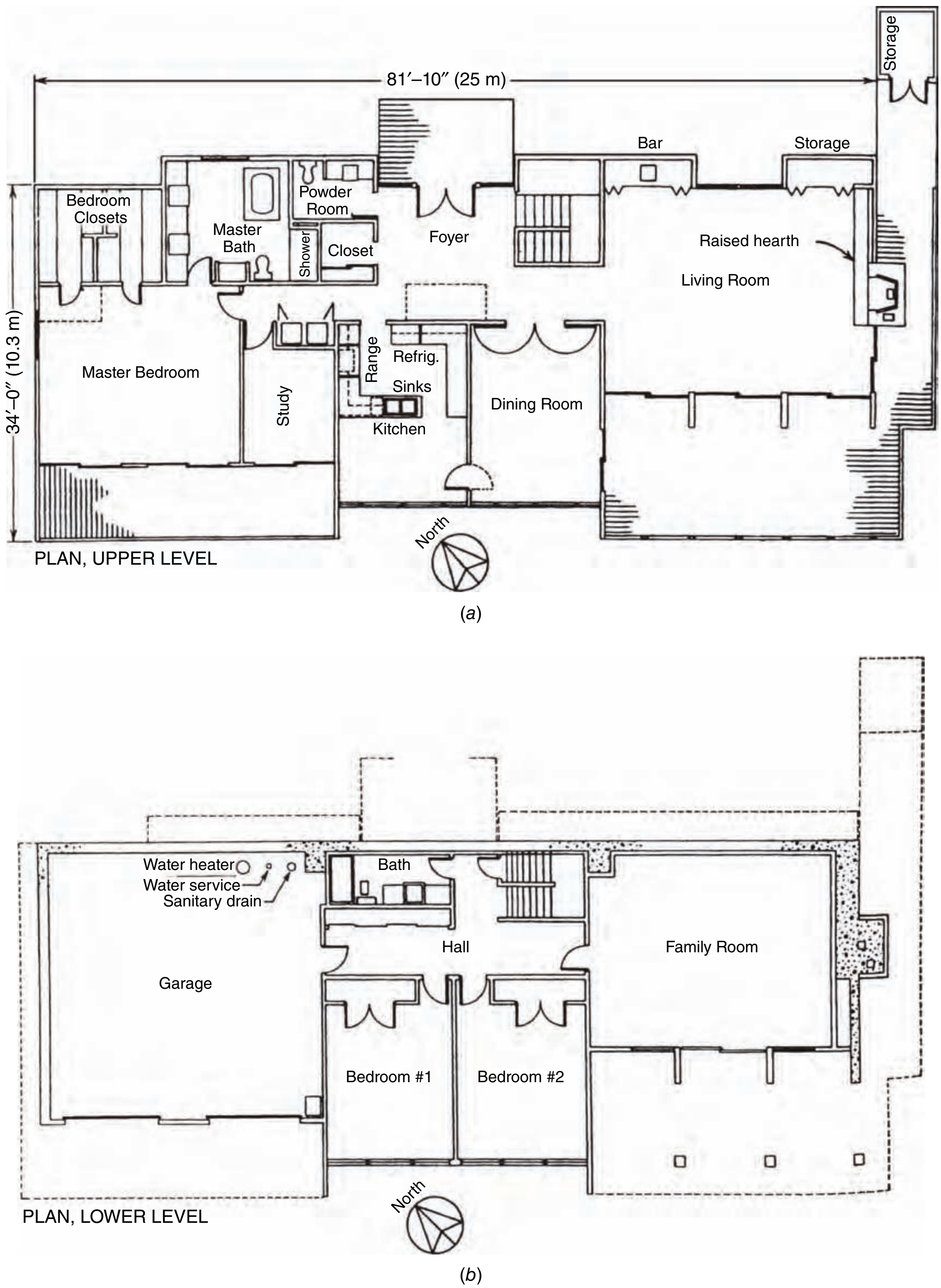


Fig. 20.22 *Example 20.1. Floor plans of a house on Long Island, New York. (Courtesy of Budd Mogensen, architect and planner.)*

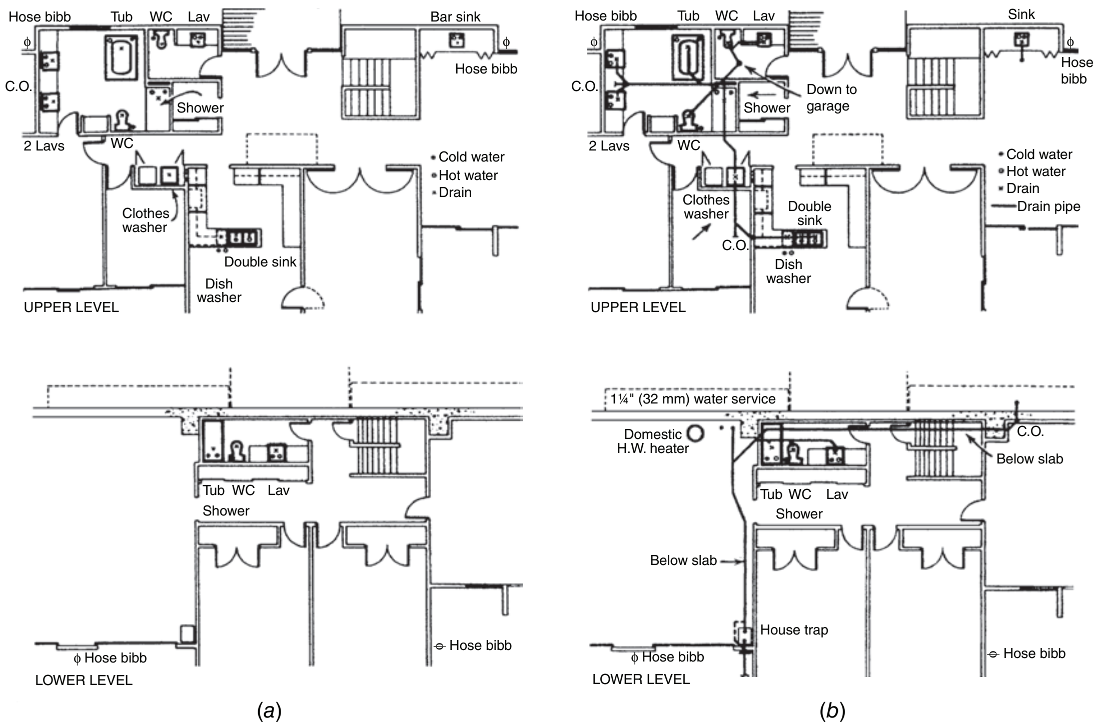


Fig. 20.23 *Example 20.1. (a) Plumbing requirements, water supply, and partial sanitary drainage. (b) Sanitary drainage plan.*

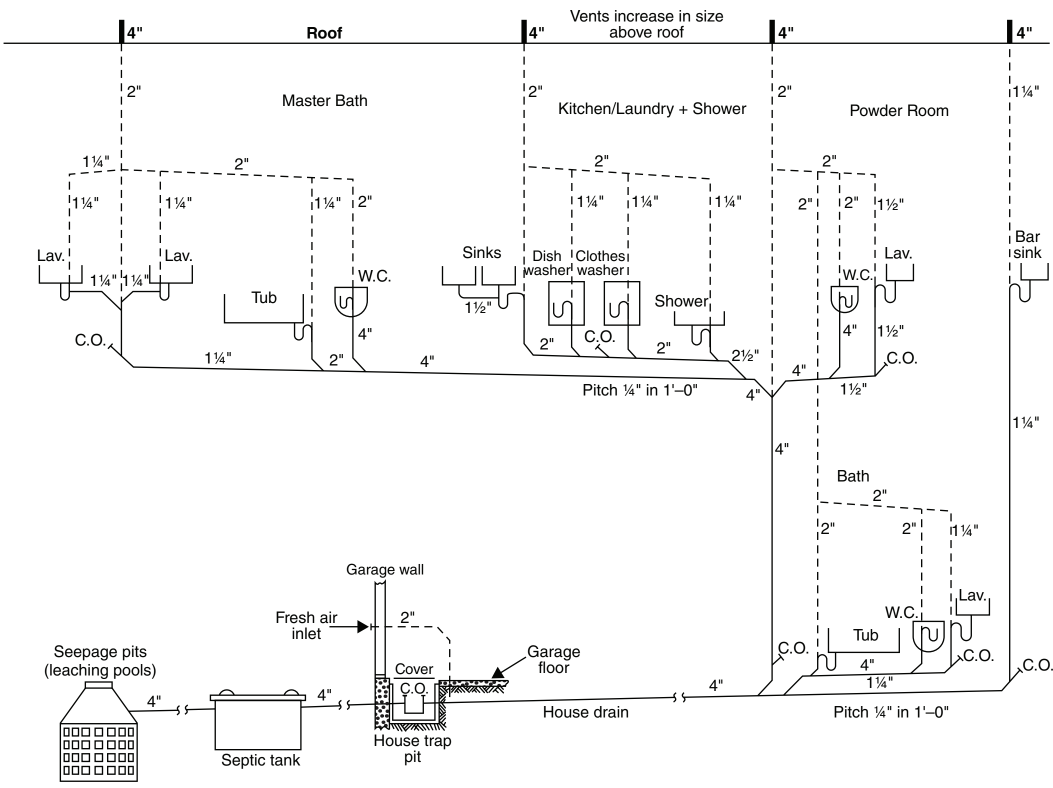


Fig. 20.24 *Example 20.1. Plumbing section. When every fixture is vented individually, as in this example, the method is known as* continuous venting. *In larger systems, groups of fixtures may be vented by a loop or circuit vent. This reduces the amount of piping in the vent system (see Figs. 20.10 and Fig. 20.29). Note that septic tank discharge to a leaching pit is not permitted in many locations; see Section 20.6.*

TABLE 20.6 Drainage Fixture Units (DFU) for Example 20.1

Residential Fixture	Drainage Fixture Units (dfu)
Bar sink	2
Kitchen sink with dishwasher	2
Lavatory	1
Water closet	4
Automatic clothes washer	2
Master bathroom group (WC >1.6 gpf [6 Lpf])	6
Extra lavatory	1
Shower	2
Lower floor bathroom group (WC >1.6 gpf [6 Lpf])	6
Total	**26**

DFU values are from Table 20.2. The hose bibb drains to the ground; roof drainage is taken to dry wells.

Fig. 20.25 *Plumbing risers in a fireproof multistory building. Pipes, tubes, conduits, and ducts adjoin toilet rooms and utility spaces. Ventilation ducts and a master 5-in. (127-mm) copper hot-water riser are just to the left of center. Soil and vent stacks with hot and cold water supplies—all copper— are to the right of this group. At the left, in a lighter tone, are the galvanized steel feeder conduit and the distribution circuit conduits for a local electrical control panel box. Note that some pipes and tubes are supported at this floor by bolted clamps. After testing and before pipes are enclosed, covering will be completed. (Courtesy of Copper Development Association.)*

Table 20.3 indicates that a 3-in. (76-mm) horizontal fixture branch is inadequate for the men's toilet group because this size pipe will handle only 20 dfu. Therefore, a 4-in. (102-mm) pipe is selected (also a wise minimum choice whenever water closets are served). Its capacity of 160 dfu will be more than enough for the 36 fixture units needed here. The same table shows that the soil stack diameter can be 4 in. (102 mm), and it is run thus for its entire height. Its capacity of 90 dfu per story (or interval) is sufficient for the 64 dfu that connect in at each T-Y connection. For three branch intervals, this size stack will carry 240 dfu (this example requires 3 × 64 = 192 dfu); for its entire height, it will carry 500 dfu (this example requires 5 × 64 = 320 dfu).

The vent stack must serve up to 338 dfu, with a 4-in. (102-mm) soil stack, and with a maximum 70-ft (21.3-m) developed length. From Table 20.4, a 3-in. (76-mm) vent serving 540 dfu has a maximum developed length of 150 ft (45.7 m), well over the minimum requirements. All vent stack diameters will increase to 4 in. (102 mm) as they pass through the roof.

According to Table 20.5, the building drain and the building sewer, at a pitch of ¼ in. per foot (2.1%), should carry at least a total of 350 dfu. A 5-in. (127-mm) building drain or building sewer has a capacity of 480 dfu.

Although opinions may vary about the relative merits of continuous or circuit venting, either system, properly designed, will effectively prevent the siphoning of traps and relieve air pressures that could cause foul gases to bubble through the traps into the occupied space. Another system (Section 20.5c), especially suitable for high-rise buildings, eliminates the vent stack completely with equal effectiveness. ■

(c) The Sovent System

This essentially ventless system changes the nature of the effluent (the wastes discharged from the fixtures) instead of coping with the pressures and suctions that normal effluent would cause (see Figs. 20.30 and 20.31).

The "plunger" effect of a descending "slug" of water/waste within pipes was described in Section 20.2. If the "effectiveness" of the plunger can be reduced, the negative and positive pressures created by it will also be reduced. If their values can be brought down below the holding power of the several inches of water in the trap, no vents will be

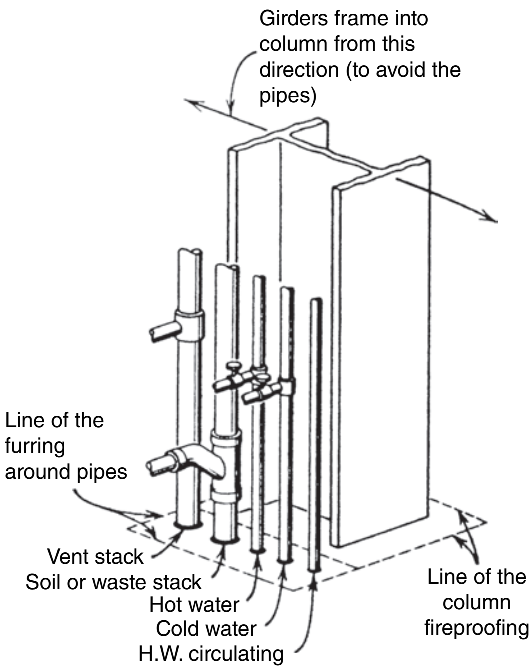
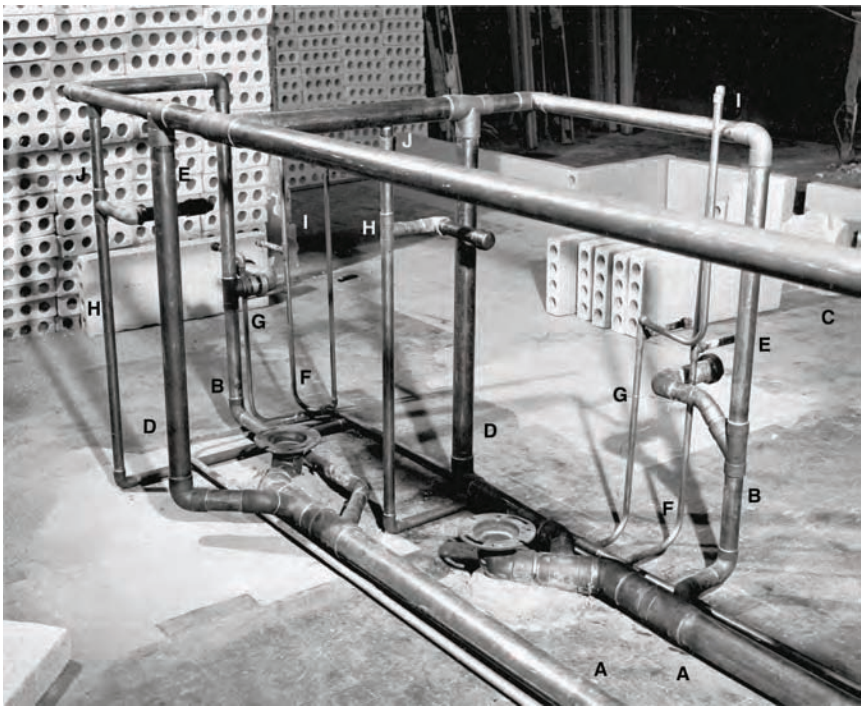
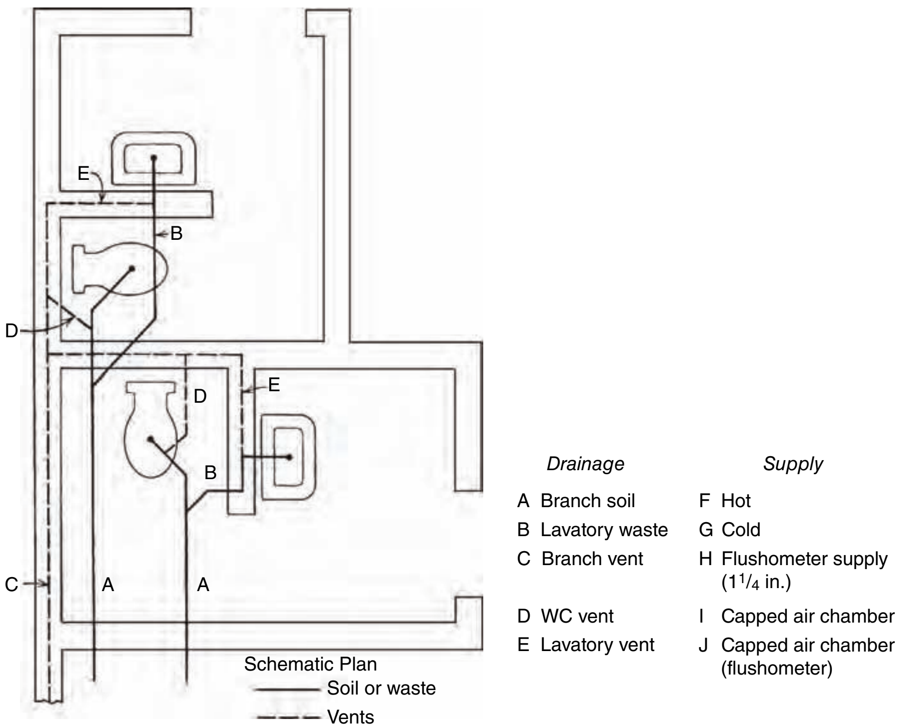


Fig. 20.26 *Piping at a "wet" column. In large office buildings, there are usually several of these, remote from the core, in the general office area.*



(*a*)

Fig. 20.27 *(a) Horizontal waste piping* above *the structural slab, in an example of roughing-in plumbing for two lavatory rooms in a concrete office building. A lavatory and water closet (WC) in each room (see plan in b) are served by soil and waste branches below and vent branches above. Hot- and cold-water tubing with air chambers can be seen. Although the extensions of the water tubing above the two flushometer connections appear to connect into the horizontal vent branches, they actually do not; they are capped and merely touch the bottoms of the vent branches. Note that soil branches are above the structural slab. A fill of 5 or 6 in. (125 to 150 mm) is necessary to cover the tubing. All vertical tubing will be within the masonry block used to enclose the cubicles. (Courtesy of the Copper Development Association.)*



(*b*)

Fig. 20.27 *(Continued)*

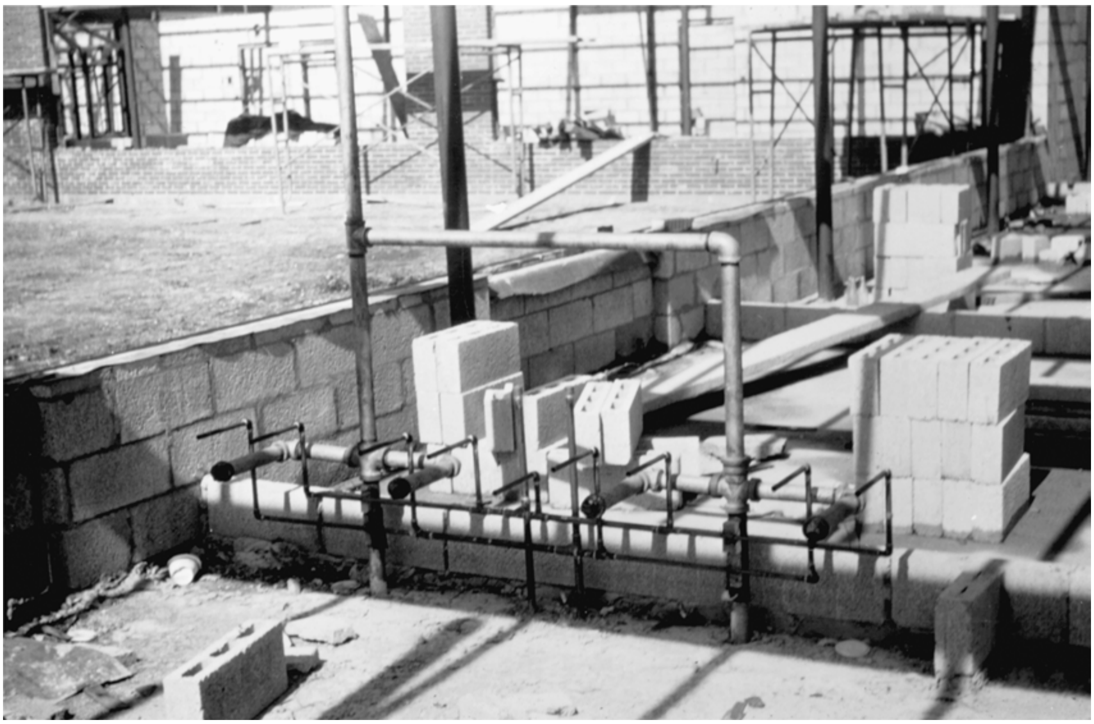


Fig. 20.28 *Roughing-in plumbing for four lavatories in the toilet room of a school. The waste branches have been capped and the system tested for leakage. The waste branches are cast iron, the vents galvanized steel, and the water supply lines are copper with soldered fittings. At the center of the supply array are vertical capped expansion and shock tubes, one for hot and one for cold supply water.*

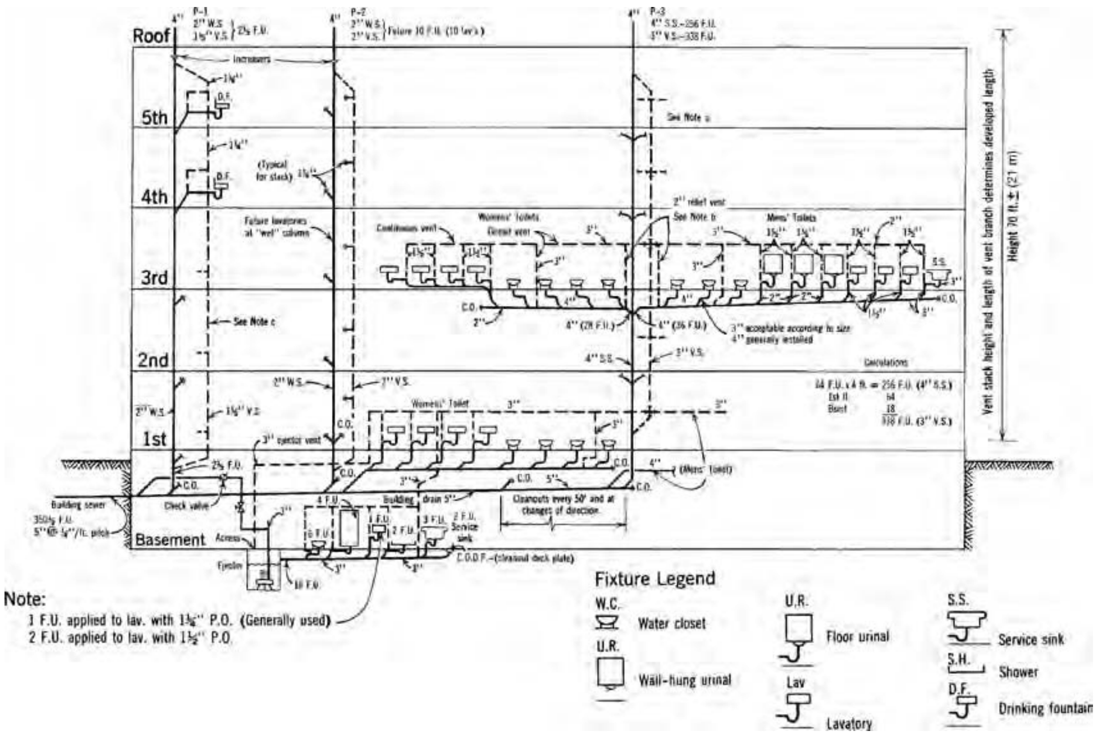


Fig. 20.29 *Example 20.2. Plumbing section of an office building. Circuit vents serve branch soil lines, but some codes require continuous venting (individual fixture vents). The house trap and fresh-air inlet are omitted from the building drain. Note that (1) a relief vent is not required on the top floor. (2) Men's and women's toilets on the third floor are typical and would be repeated on the first, second, fourth, and fifth floors. (3) Drinking fountains on the fifth and fourth floors would be repeated on the first, second, and third floors.*

necessary. In the single-stack *Sovent* system illustrated in Fig. 20.31, this is done by dealing with the normal liquid effluent at each floor. Aeration there produces a *foam* that lacks the stack-filling tendency of unaerated liquid effluent. Thus, through the creation of a *soft* plunger, pressure variations in the single stack are minimized.

Tests have shown that the positive and negative pressures produced by normal liquid effluent during its descent (to be relieved by the vent piping) are often about 5 to 12 in. (127 to 305 mm) water gauge. If vents were not provided, the 2 to 4 in. (51 to 102 mm) of water seal in the traps would be vulnerable to penetration by gases from pipes under greater positive pressure (or siphonage of water seals into pipes that may be under negative pressure).

Figures 20.30, 20.31, and 20.32 illustrate the components and the action of the Sovent system. Effluent, already aerated and descending from upper stories, is diverted in the stack at each lower story. The aerator fitting there affords a passage for this diverted flow and also an air space into which the effluent from the local branch soil or waste can drop. Here it spatters, mixing with air to form a rarefied mixture of air and liquid. Tests show that this mixture does not produce pressures, positive or negative, of more than 1 in. (25 mm) on the water gauge. Thus, a trap seal of 2 in. (51 mm) or more is safe against siphonage or penetration.

At the foot of the single stack the aerated effluent is compacted—a process aided by a baffle in the path of the flow in the deaerator fitting (see Fig. 20.32). If not relieved, air piling up at this point could cause pressures in the stack at the first floor. An air-discharge pipe provides relief of air from the deaerator fitting to the upper part of the building drain, above the liquid flow.

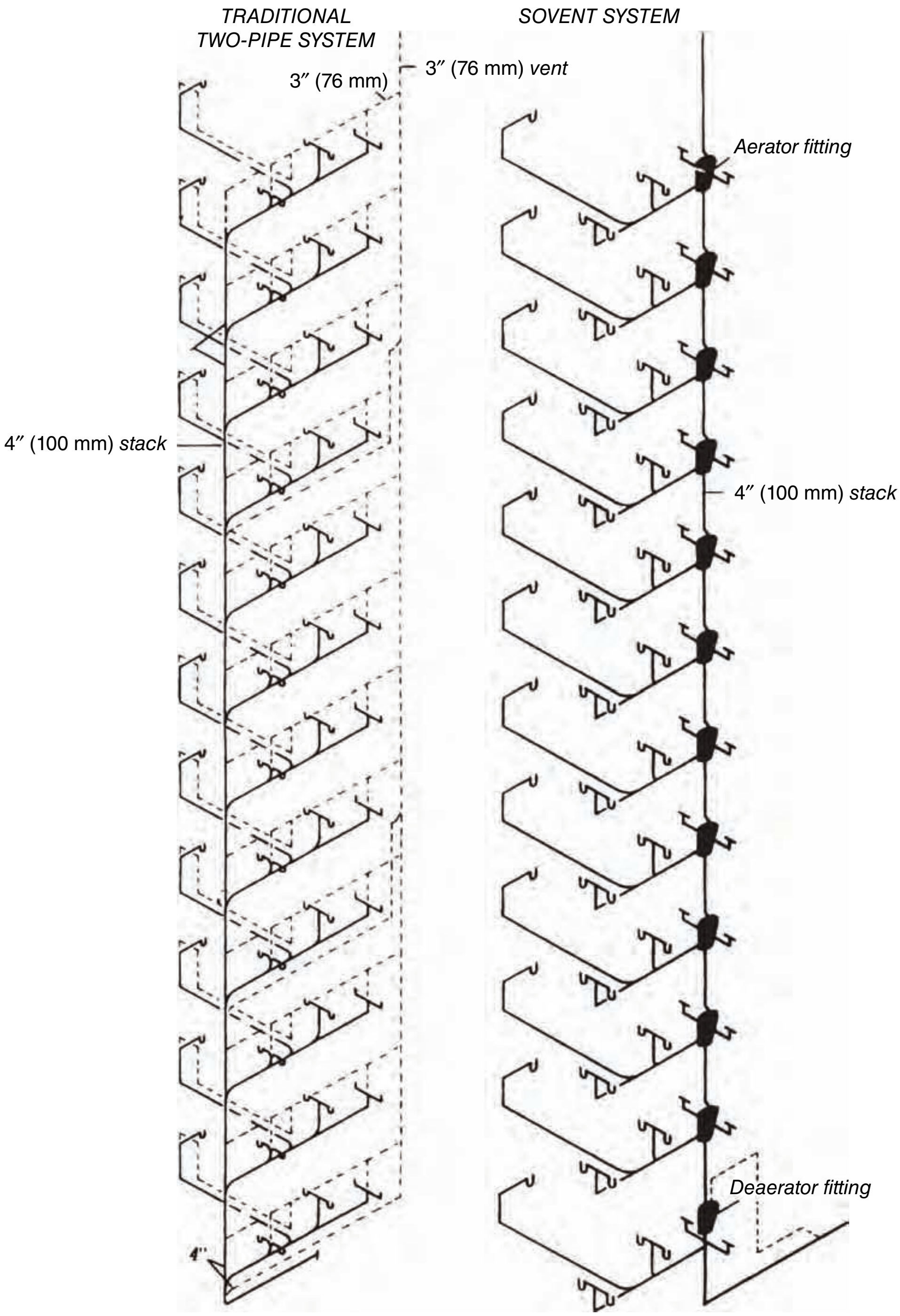


Fig. 20.30 *Comparing a two-pipe system for a 12-story stack serving an apartment grouping to the Sovent system. (Courtesy of the Copper Development Association.)*

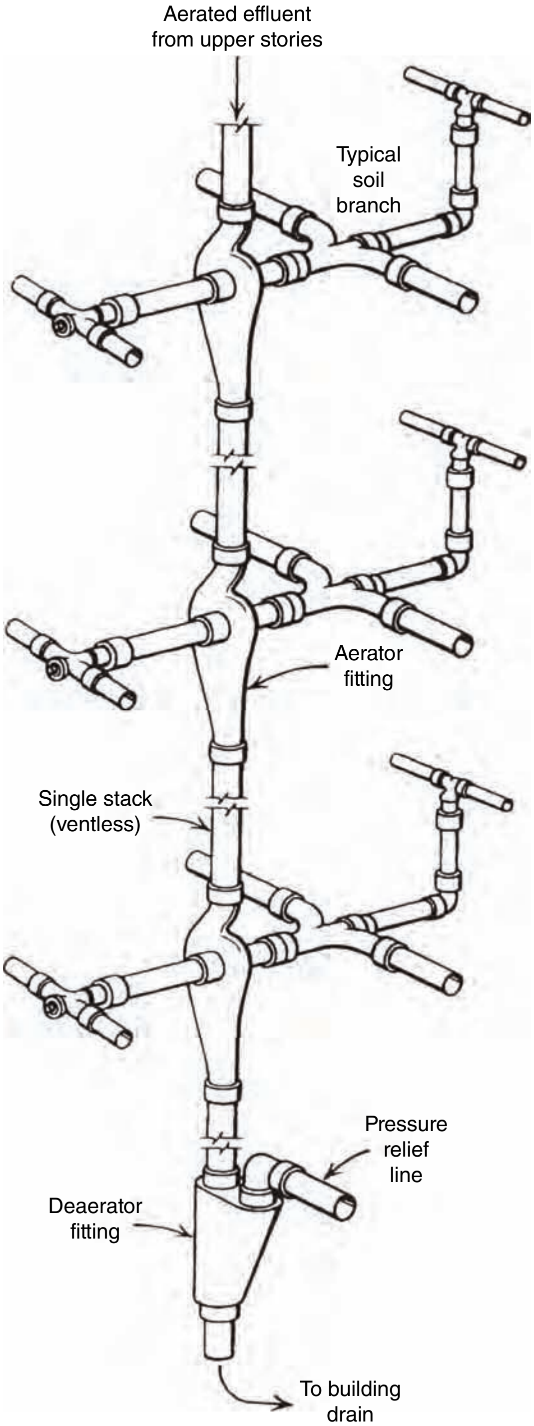


Fig. 20.31 *The Sovent drainage stack consists of aerator fittings that join the horizontal branches to the stack at each floor level and a deaerator fitting at the bottom of the stack. The stack is open to the atmosphere above the roof at the top. (Courtesy of the Copper Development Association.)*

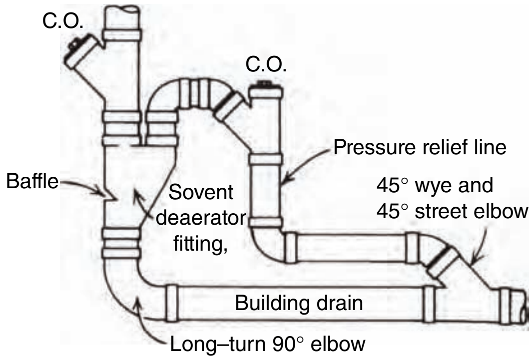


Fig. 20.32 *The deaerator consists of an air separation chamber with an internal nosepiece, a stack inlet, a pressure relief outlet at the top, and a stack outlet at the bottom. The deaerator fitting at the bottom of the stack functions in combination with the aerator fittings above to make the single stack self-venting. The deaerator is designed to overcome the tendency for the falling waste to build up excessive back pressure at the bottom of the stack when the flow decelerates at the bend into the horizontal drain. (Courtesy of the Copper Development Association.)*

The Sovent system was invented by Fritz Sommer of Switzerland, who tested it in a 10-story drainage test tower. Since its introduction in 1962, it has been installed and used in hundreds of buildings in Europe and Africa. Canada used the Sovent method in the Habitat apartments at the 1967 Montreal exposition. Sovent was first granted U.S. code acceptance in 1968 in Richmond, California. Following this success, its code acceptance grew rapidly during the early 1970s. However, not all jurisdictions allow Sovent installations.

20.6 ON-SITE INDIVIDUAL-BUILDING SEWAGE TREATMENT

The great majority of stand-alone building sewage treatment systems in North America use a septic tank (Fig. 20.33) as a *primary* treatment device, where the settling of solids and anaerobic digestion take place. Subsequently, the effluent receives *secondary* treatment, which usually consists of a filtering process. Four common filtration systems are seepage pits, drain fields, mounds, and sand filters. Occasionally, a *tertiary* treatment (usually disinfection with chlorine) must be used, as when outflows from secondary treatment will flow directly into surface waterways.

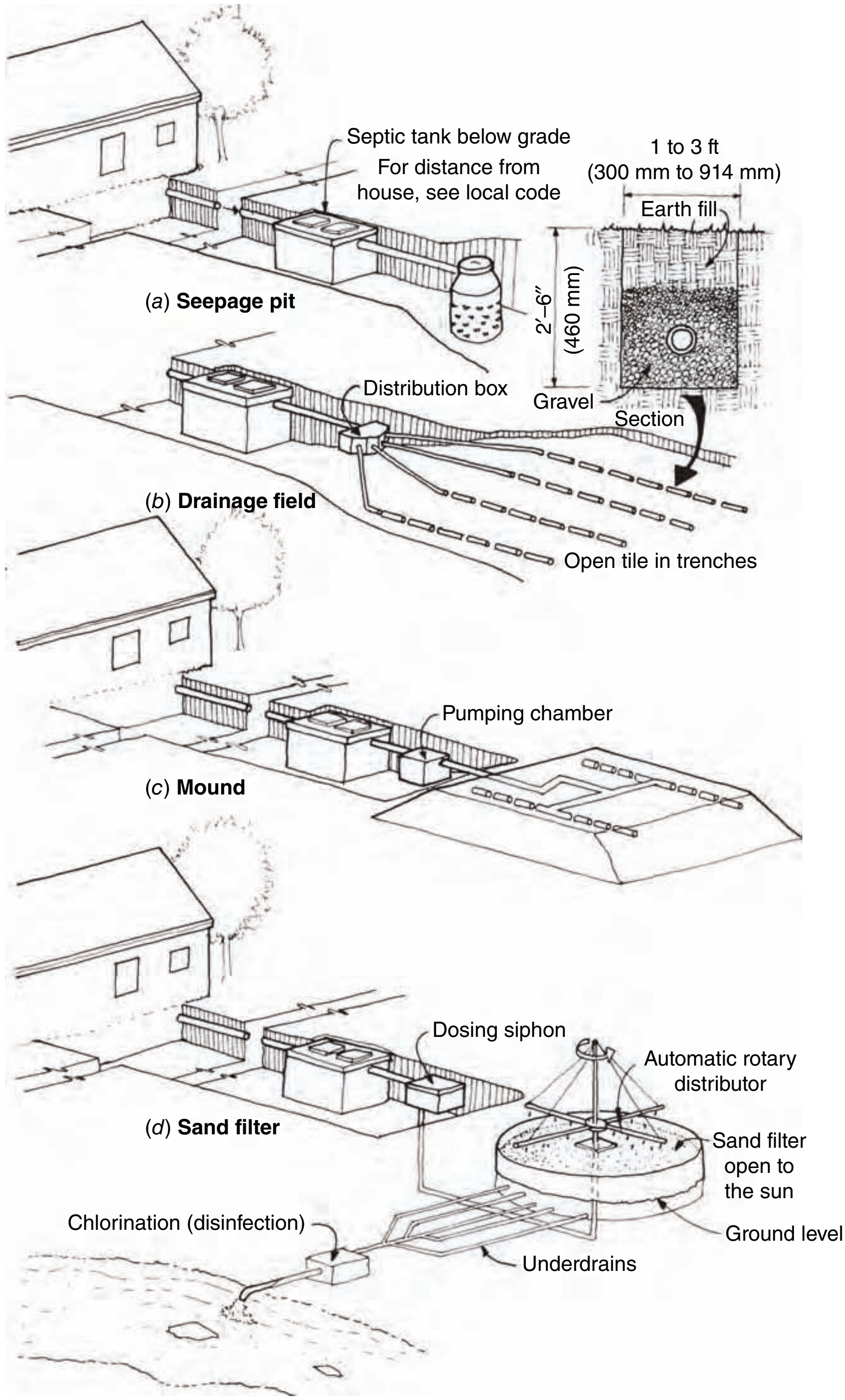
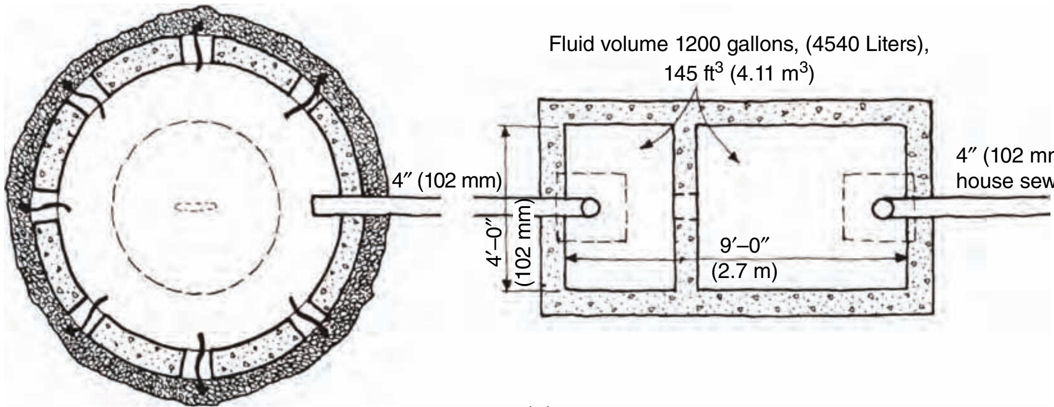


Fig. 20.33 *For individual sewage treatment systems, septic tanks are commonly used for primary treatment. Four options for secondary treatment are shown here. (Tertiary treatment usually is required only for effluent discharge into waterways.) (a) Seepage pits are rarely allowed. (b) Drain fields are the most commonly used options. (c, d) Mounds and sand filters are more expensive to construct and are used where high water tables preclude the use of option (b).*

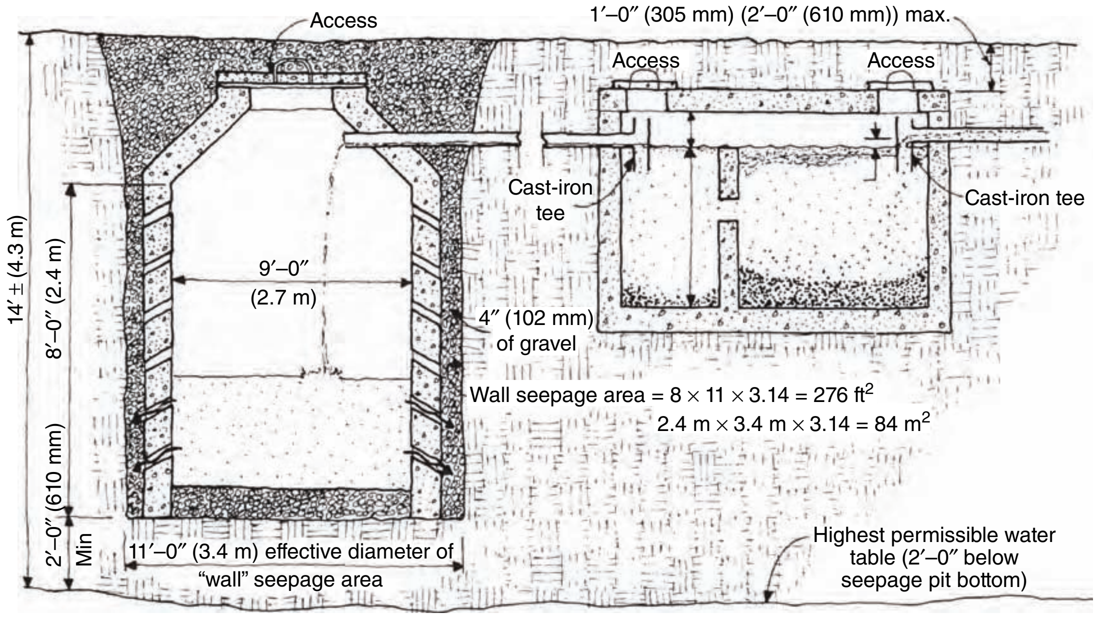
(a) Primary Treatment: Septic Tanks

These (Fig. 20.34) are commonly constructed of precast concrete, although steel, fiberglass, and polyethylene tanks are also available. The sewage enters the first chamber, where solids sink to the bottom as sludge, and scum forms on the surface. Anaerobic decomposition proceeds, producing methane gas. The liquid moves through the submerged opening in the middle of the tank to the second chamber, where finer solids continue to sink, and less scum forms on the surface. Finally, the effluent, about 70% purified, leaves the septic tank for secondary treatment.

The longer the sewage stays in the septic tank, the less polluted the effluent. This is why water conservation measures are so welcome with septic tank systems; the less the flow, the longer the water remains in the tank. The anaerobic



(*a*)



(*b*)

Fig. 20.34 *Plan (a) and section (b) of a septic tank and seepage pit for a four-bedroom house in sandy loam soil. A pit is suitable only when the earth is absorbent and the water table low (below the pit bottom). The drawing is not to scale.*

decomposition process, while malodorous, is so thorough that the sludge needs only occasional removal—once in several years is about average for residences. The methane and its odor are kept within the tank, and access hatches are sometimes covered with soil (as in Fig. 20.34), even though this makes their occasional need to be located far more difficult.

Most systems with septic tanks will eventually experience failure, usually due to a breakdown in the secondary treatment rather than in the septic tank. With periodic removal of sludge, the septic tank itself is a reliable and simple primary treatment device. However, some types of domestic waste can disrupt the anaerobic process within the tank. The worst offenders are paints, varnishes, thinners, waste oil, photographic solutions, and pesticides. Also to be avoided are coffee grounds, dental floss, disposable diapers, kitty litter, sanitary napkins, tampons, cigarette butts, condoms, gauze bandages, fat and grease, and paper towels.

Septic tank sizes are commonly based on code requirements that consider the number of bedrooms in residences (Table 20.7), or the number of waste fixture units served (see Table 20.2). (As shown in Table 20.8, maximum size may also be related to the soil condition.) Sewage flow rates are also considered. Oversized septic tanks are more expensive to install, but they release cleaner effluent and prolong the life of the secondary treatment system.

The size of the secondary treatment system is usually based upon the size of the septic tank it serves or on the expected total flow over a 24-hour period. (Flow can be estimated from Table 18.4.) Where effluent must be raised for secondary treatment, or when the total length of the secondary treatment disposal line exceeds 500 ft (154 m), a dosing tank (also called a *siphon* or *pumping chamber*; see Fig. 20.33*c*, *d*) is used to automatically discharge the septic tank's outflow chamber to the secondary treatment lines or sand filters.

TABLE 20.7 Septic Tank Capacity[a]

Single-Family Dwellings—Number of Bedrooms	Multiple-Dwelling Units or Apartments—One Bedroom Each	Other Uses: Maximum Fixture Units Served[b, c]	Minimum Septic Tank Capacity, Gal (L)[c]
1 or 2		15	750 (2838)
3		20	1000 (3785)
4	2 units	25	1200 (4542)
5 or 6	3	33	1500 (5678)
	4	45	2000 (7570)
	5	55	2250 (8516)
	6	60	2500 (9463)
	7	70	2750 (10,409)
	8	80	3000 (11,355)
	9	90	3250 (12,301)
	10	100	3500 (13,248)
Extra bedroom: 150 gal (568 L) each.			
Extra dwelling units over 10: 250 gal (946 L) each.			
Extra fixture units over 100: 25 gal (95 L) per fixture unit.			

Source: ©2012 *Uniform Plumbing Code*. Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

[a]Septic tank sizes in this table include sludge storage capacity and the connection of domestic food waste disposal units without further volume increase.

[b]See Table 20.2.

[c]For larger or nonresidential installations in which sewage flow rate is known, size the septic tank as follows:

1. Flow up to 1500 gpd (5678 L/d): flow × 1.5 = septic tank capacity
2. Flow over 1500 gpd (5678 L/d): (flow × 0.75) + 1125 = septic tank capacity in gallons [(flow × 0.75) + 4258 = capacity in liters]
3. Secondary system shall be sized for total flow per 24 hours.

TABLE 20.8 Septic Tank and Leaching Area Design Criteria for Five Typical Soils

Type of Soil	Required ft^2 of Leaching Area per 100 gal (m^2/L)	Maximum Absorption Capacity, gal/ft^2 of Leaching Area for a 24-h Period (L/m^2)	*Maximum Septic Tank Size Allowable*	
			Gallons	Liters
1. Coarse sand or gravel	20 (0.005)	5 (203.7)	7500	28,387
2. Fine sand	25 (0.006)	4 (162.9)	7500	28,387
3. Sandy loam or sandy clay	40 (0.010)	2.5 (101.9)	5000	18,925
4. Clay with considerable sand or gravel	90 (0.022)	1.10 (44.8)	3500	13,247
5. Clay with small amount of sand or gravel	120 (0.029)	0.83 (33.8)	3000	11,355

Source: ©2012 *Uniform Plumbing Code*. Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

(b) Primary Treatment: Aerobic Treatment Units

Active aerobic treatment units (ATUs, Fig. 20.35) are an increasingly popular alternative to septic tanks for primary sewage treatment. They are frequently used to replace a passive septic tank in a troubled system; this "upgrade" can rejuvenate an existing drain field and extend its life. ATUs depend upon air bubbled through the sewage to achieve aerobic digestion, which is faster than anaerobic digestion; hence, they can be smaller than septic tanks. They are energy-intensive and require more maintenance than anaerobic tanks. A secondary treatment process is required as well. The effluent typically is less polluted than that of septic tanks; the biochemical oxygen demand (BOD) is reduced by 90% in ATUs compared to the 50% typical of septic tanks.

The sewage first enters an aeration chamber, where it is kept in turmoil so that air can continue to percolate through it. Either air is forced through the sewage by distribution lines fed by an air compressor or the sewage is stirred by a variety of devices, depending upon the manufacturer. After about a day's retention in the aeration chamber, the aerated wastewater enters a settling chamber, allowing remaining solids to settle and to be filtered out before the effluent leaves, for further treatment in a secondary process.

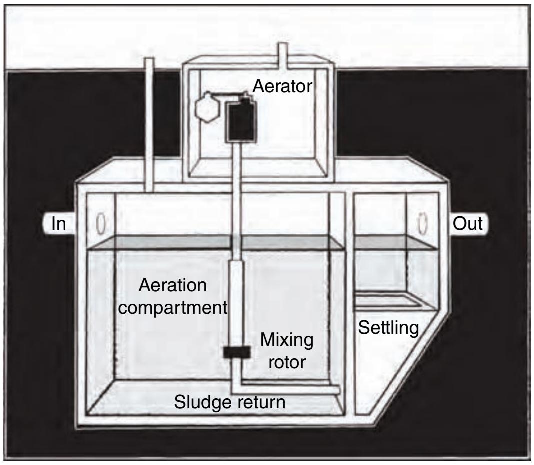


Fig. 20.35 *Aerobic treatment unit (ATU), requiring more energy and maintenance, but with cleaner effluent than that of a passive anaerobic septic tank. (National Small Flows Clearinghouse.)*

(c) Secondary Treatment: Seepage Pits

Also called *cesspools* (Fig. 20.36), these follow treatment by either septic tanks or ATUs. They are increasingly rare, and are appropriate only in very porous soil, where the water table is at least 2 ft (0.6 m) below the bottom of the pit. Because these pits are commonly 10 to 15 ft (3 to 4.6 m) below the earth's surface, a very low water table may be required. Another common usage of precast seepage pits is for *dry wells* that receive runoff from paved areas during rainstorms.

Seepage pits are sized by the square footage of the wall area exposed to the earth—the *leaching area*, as listed in Table 20.8. Placement of pits relative to buildings, water sources, waterways, and property lines is strictly controlled—see Table 20.9 and Fig. 20.36.

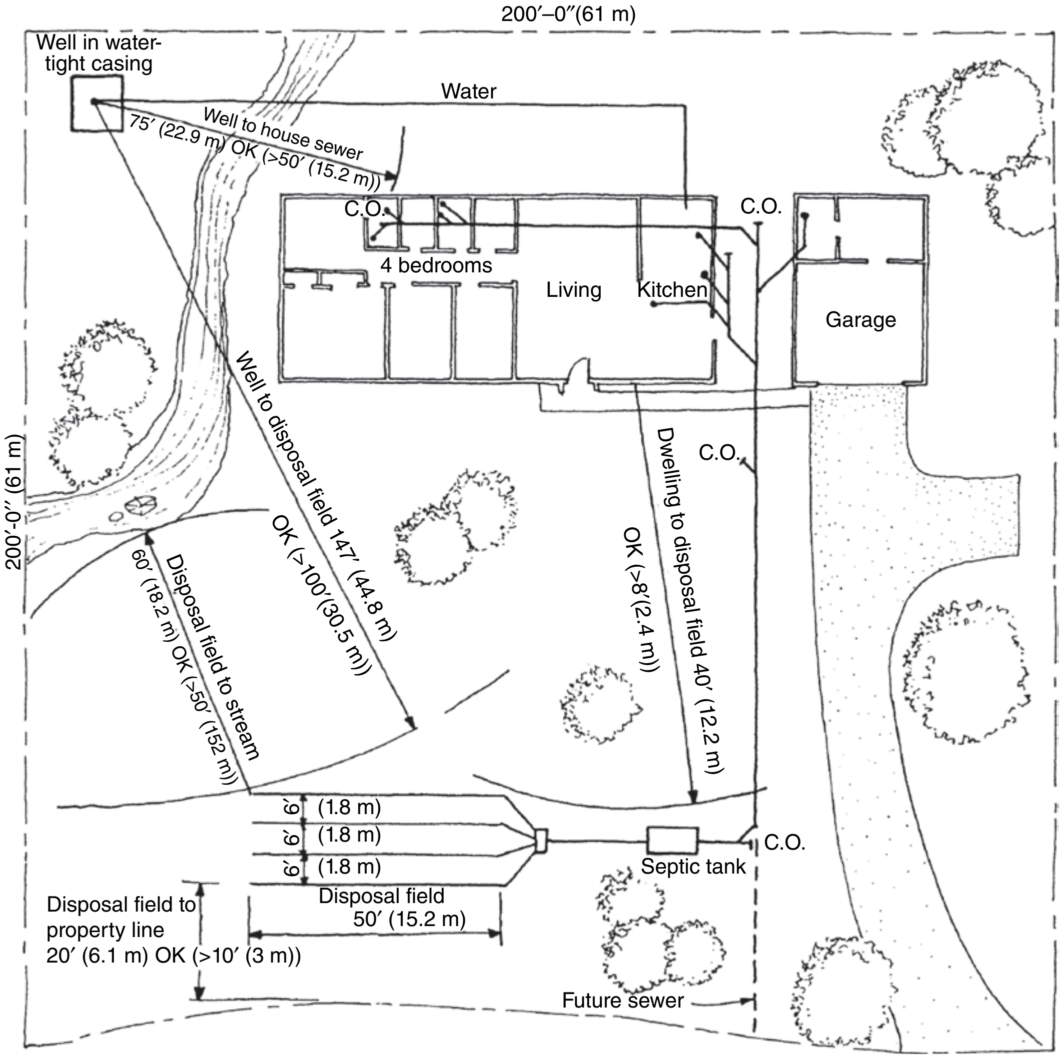


Fig. 20.36 *Checking for required clearances on a suburban lot. Although the 40,000-ft² (3716-m²) lot is more than the minimum required, space should be left for a backup disposal field (of equal size) in case of failure of the original field.*

(d) Disposal Fields

These are very commonly used as a secondary treatment method (Fig. 20.37) because they are relatively inexpensive to build and do not require a water table so deep—or soil so permeable—as do seepage pits. Drain lines consisting of either perforated pipes (of many approved materials) or square-edge agricultural tile that is 4 in. (102 mm) or more in diameter (with the ends of the tiles separated by ¼-in. [6-mm] openings) are typically used. These lines are placed in shallow trenches, on a bed of gravel, and covered with gravel. The effluent runs out of these lines and stands in the interstices of the gravel until it seeps into the earth. In effect, the gravel provides a space that acts as a dry well—receiving the fluids and accommodating them until they slowly sink into the ground.

Disposal fields are located according to regulations such as those given in Table 20.9 and sized in relation to total sewage flow and septic tank size (see Tables 20.8 and 20.10). Although Table 20.8 shows the maximum absorption

TABLE 20.9 Location of On-Site Sewage Disposal Systems

Minimum Horizontal Distance Clear Required from:	*Building Sewer*		*Septic Tank*		*Disposal Field*		*Seepage Pit (Cesspool)*	
	ft	mm	ft	mm	ft	mm	ft	mm
Buildings or structures[a]	2	610	5	1542	8	2438	8	2438
Property line adjoining private property	Clear		5	1542	5	1542	8	2438
Water supply wells	50[b]	15,240	50	15,240	100	30.5 m	150	45.7 m
Streams	50	15,240	50	15,240	50	15,240	100	30.5 m
Trees	—	—	10	3048	—		10	3048
Seepage pits or cesspools	—	—	5	1542	5	1542	12	3658
Disposal field	—	—	5	1542	4[d]	1219	5	1542
On-site domestic water service line	1	305	5	1542	5	1542	5	1542
Distribution box	—	—	—		5	1542	5	1542
Pressure public water main	10[c]	3048	10	3048	10	3048	10	3048

Source: ©2012 *Uniform Plumbing Code*. Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

Note: When disposal fields and/or seepage pits are installed in sloping ground, the minimum horizontal distance between any part of the leaching system and the ground surface shall be 15 ft (4.6 m).

[a]Including porches and steps, whether covered or uncovered, breezeways, roofed porte-cocheres, roofed patios, carports, covered walks, covered driveways, and similar structures or appurtenances.

[b]All drainage piping shall clear domestic water supply wells by at least 50 ft (15.2 m). This distance may be reduced to not less than 25 ft (7.6 m) when the drainage piping is constructed of materials approved for use within a building.

[c]For parallel construction. For crossings, approval by the Health Department shall be required.

[d]Plus 2 ft (0.6 m) for each additional 1 ft (0.3 m) of depth in excess of 1 ft (0.3 m) below the bottom of the drain line.

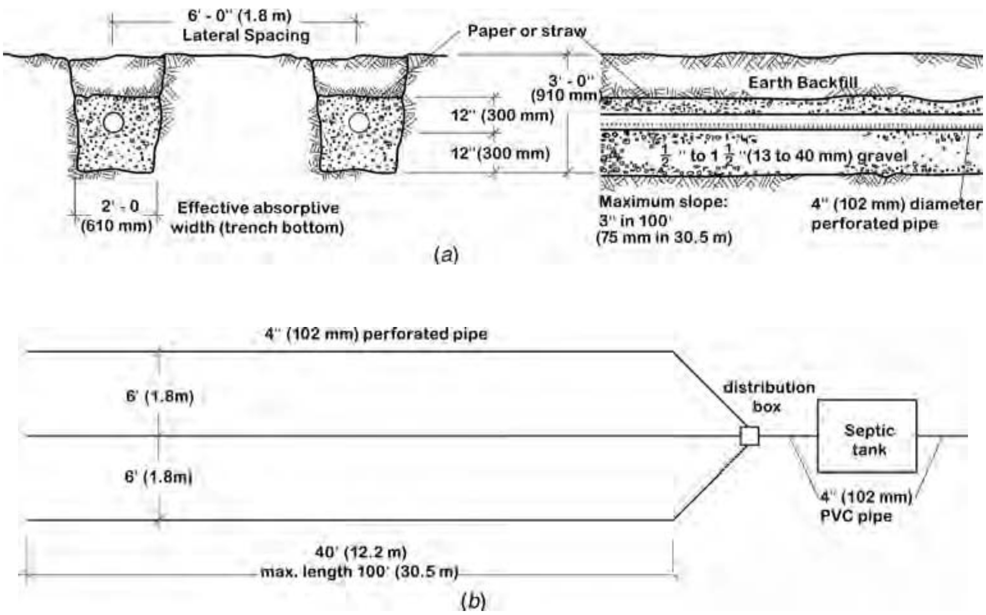


Fig. 20.37 *Example 20.3. Tile drain field for a four-bedroom house. Although the drawings are not to scale, the dimensions show a required area of about 20 ft × 50 ft (6 m × 15 m) on the lot. Because paving is not permitted over drain fields, sewage treatment on a small lot demands considerable creativity. (a) Transverse and longitudinal sections. (b) Schematic plan. (Redrawn with SI units by Nathan Majeski.)*

TABLE 20.10 Disposal Field Trenches

PART A. DIMENSIONS		
	Minimum	**Maximum**
Length of drain line(s)	—	100 ft (30.5 m)
Bottom width of trench	18 in. (457 mm)	36 in. (0.9 m)
Spacing of lines, on center (o.c.)[a]	6 ft (1.8 m)	—
Depth of earth cover over lines	12 in. (305 mm) *Note:* 18 in. (457 mm) preferred	—
Grade of lines	Level	3 in./100 ft (25 mm/m)
Filter material		
Over drain lines	2 in. (51 mm)	—
Under drain lines[a]	12 in. (305 mm)	—[d]
PART B. LEACHING AREAS		
Trench bottom[b]: minimum 150 ft^2 (14 m^2) per system Trench side wall: minimum[c] 2 ft^2/ft of length maximum[d] 6 ft^2/ft of length		

Source: ©2012 *Uniform Plumbing Code*. Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

[a]Minimum spacing of drain lines: 4 ft (1.2 m) plus 2 ft (0.6 m) for *each* additional foot (0.3 m) of depth *beyond* 1 ft (0.3 m) below the bottom of the drain line.

[b]Exclusive of rock, clay, or other impervious formations.

[c]Based on the minimum 12-in. (305-mm) trench depth below drain tile.

[d]A maximum 36-in. (0.9-m) trench depth below the drain line can be counted when calculating the required absorption area.

capacities for soils based on gal/ft^2 (L/m^2) over a 24-hour period, a common alternative is to use *percolation* tests. For such tests, a trial pit is dug and water poured into it. The absorption in gal/ft^2 (L/m^2) over a 24-hour period is determined from this test. Some codes require design sizes based upon percolation test data. Codes often require that an area equal to the prescribed drainage field size be set aside for use in the event of failure in the original field.

Design guidelines for sizing disposal fields were presented in Section 18.3, but a more detailed method is shown here. The trench width, depth, and spacing shown in Fig. 20.37 are typical, but other combinations can be used, provided that they meet the requirements listed in Table 20.10.

EXAMPLE 20.3 See Fig. 20.37. Design a septic tank and drain field system for a suburban residence under the following conditions:

Bedrooms	4
Soil	Sandy loam
Depth to water table	7 ft (2.1 m)

SOLUTION

Septic tank capacity (Table 20.7) = 1200 gal (4542 L). Fluid volume of the tank (minimum required) is

$$1200 \text{ gal} \div 7.48 \text{ gal/ft}^3 = 160 \text{ ft}^3$$
$$(4542 \text{ L}) \div 1000 \text{ L/m}^3 = 4.5 \text{ m}^3$$

Dimensions for a tank are chosen:

$$4.5 \times 4.0 \times 9.0 \text{ ft} = 162 \text{ ft}^3 \text{ volume}$$
$$1.4 \times 1.2 \times 2.7 \text{ m} = 4.5 \text{ m}^3 \text{ volume}$$

162 (proposed) > 160 (the minimum required [the same conclusion with SI units])

Drain field size is established from Table 20.8: sandy loam (soil type 3) requires 40 ft^2 (3.7 m^2) of leaching area per 100 gal (378 L). With a septic tank of 1200 gal (4.5 m^3),

$$40 \text{ ft}^2 \times 1200 \text{ gal}/100 \text{ gal} = 480 \text{ ft}^2 \text{ minimum absorption area}$$
$$(3.7 \text{ m}^2 \times 4500 \text{ L}/378 \text{ L} = 44 \text{ m}^2 \text{ minimum absorption area})$$

The effective absorption area of the typical trench depth and spacing shown in Fig. 20.37 is

Trench width	2.0 ft^2/ft (0.6 m^2/m) of length
Trench sides	2.0 ft^2/ft (0.6 m^2/m) of length (12 in. [305 mm] on each side)
Total absorption	4.0 ft^2/ft (1.2 m^2/m)

The required absorption area was determined to be 480 ft^2 (44 m^2). Because the trench has 4.0 ft^2/ft (1.2 m^2/m) of length, the total trench length must be

480 ft^2/(4 ft^2/ft) of length = 120 ft
[44 m^2/(1.2m^2/m) = 37 m]

A three-line disposal field is selected, so 120 ft / (3 lines) = 40 ft (37 m / (3 lines) = 12.3 m) per line. Given the required clearances from the edges of the disposal field (Table 20.9) of 5 ft (1.5 m) to the property lines, the disposal field area can be calculated as:

width:

5 ft + 12 ft (two spaces of 6 ft each) + 5 ft = 22 ft
[1.5 m + 3.7 m (2 spaces at 1.85 m each) + 1.5 m = 6.7 m]

length:

5 ft + 40-ft line + 5 ft = 50 ft
[1.5 m + 12.3 m line + 1.5 m = 15.3 m]

The site surface area, then, is 22 ft × 50 ft = 1100 ft^2 (6.7 × 15.3 m = 102 m^2). Note that double this area (for a second disposal field in the event of failure of the first field) is often required. ■

(e) Mounds with Leaching Beds

These (Fig. 20.38) represent a newer solution in the United States and thus may require special approval. The guidelines for leaching-bed sizing are essentially similar to those for drainage tile disposal fields. The absorption area for leaching beds, however, must be 50% greater than that required for trenches. The bottom of the leaching bed generally must be at least 5 ft (1.5 m) above the water table, although in water-scarce areas, officials may reduce this requirement.

(f) Buried Sand Filters

Slow sand filters for treating supply water were discussed in Section 19.2(d) and shown in Fig. 19.3. Buried sand filters (Fig. 20.39) work in a similar way, using primarily biological but also physical and chemical processes to clean wastewater. The medium is most commonly sand, although other locally available materials such as crushed glass, mineral tailings, bottom ash, and so on, have been used. The grain size ranges from 0.01 to 0.1 in. (0.3 to 3 mm) in diameter.

The layout is similar to that of the disposal fields described in Section 20.6(e), but these filters, themselves 24 to 36 in. (610 to 914 mm) deep, usually require an excavation of 4 to 5 ft (1.2 to 1.5 m). The filter bed must be level and sited to avoid contact with groundwater and excess surface water runoff. Some authorities require the sand filter to be contained in an impermeable membrane liner. Underdrain pipes and a graded layer of washed gravel or crushed rock are placed on the bottom of the filter bed, with the finer gravel on top to keep the medium from washing into the underdrains. Then a layer of fine gravel first, with coarser gravel above, is placed around and over the distribution pipes. A geotextile fabric covers the top of the entire filter bed, which

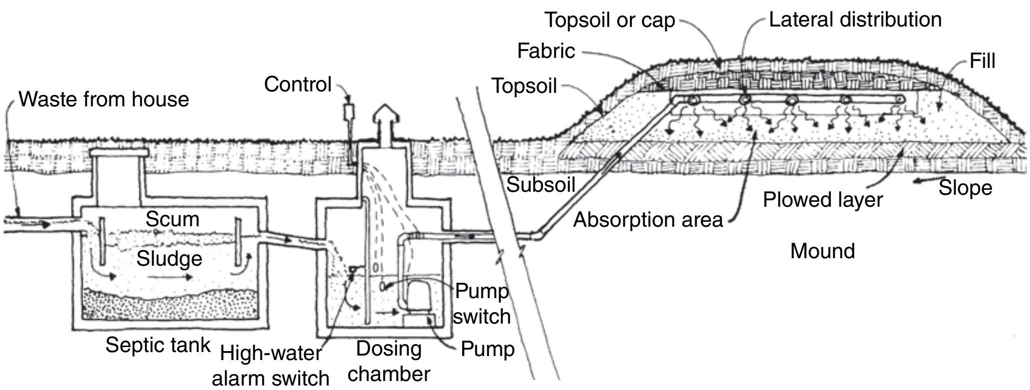


Fig. 20.38 *Mounds with leaching beds offer a disposal option when the water table is high. The system serves a two- or three-bedroom home. (Adapted from Converse, 1978)*

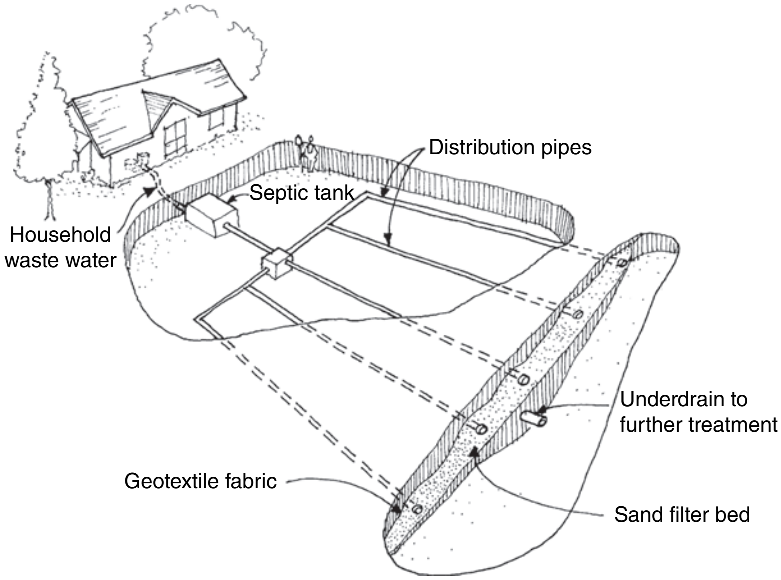


Fig. 20.39 *Buried sand filters appear to be like the common disposal fields, but are deeper and may require an impermeable membrane liner. (National Small Flows Clearinghouse.)*

in turn is covered by backfill material. A properly constructed buried sand filter that receives properly digested waste from a well-maintained septic tank should last for up to 20 years without maintenance.

Buried sand filters are one remedy for failed disposal fields. They are also used where high groundwater, shallow bedrock, or poor soil preclude use of the simpler disposal field. Although buried sand filters may require considerable site area, the ground surface can be used for lawns or other nonpaved surface activities. More detailed information on the sand filter types discussed here is available from the National Small Flows Clearinghouse.

In general, sand filters are designed for normal dosing twice a day; they need time to allow the filter medium to drain between doses. The water that filters through the medium is collected in underdrains that are sloped toward an outlet and vented to the surface at the upstream end. This vent is a potential source of odors. The water is then taken either to a disinfection (usually chlorination) unit or to a disposal field for subsurface discharge.

Water from sand filters has been cleansed of many pathogens, such as harmful bacteria and viruses, and is therefore more likely to be approved for a down-line disposal field. Typical values for three types of sand filters are shown in Table 20.11. (Open and recirculating sand filters are discussed in the next section.)

20.7 ON-SITE MULTIPLE-BUILDING SEWAGE TREATMENT

The first approach to a multiple-building treatment system involves providing septic tanks at each building for primary treatment. Then the outflows from the individual septic tanks are combined and enter a secondary treatment process. Either of two specific types of sand filters can be employed for this purpose. There are several advantages to this approach. The effluent lines from the septic tanks carry no solids; they can be much smaller in diameter and placed in shallower trenches than conventional sewer lines. The runs are far shorter, because distant centralized treatment plants are not involved. With sand filter secondary treatment, the septic tank wastewater is more likely to find a recycling use, such as irrigation.

(a) Open Sand Filters

Also called *intermittent sand filters*, these are very similar in construction to slow sand filters

TABLE 20.11 Sand Filter Design Values[a]

Design Factor	Buried Filters	Open Filters	Recirculating Filters
Pretreatment	All filters must be preceded by settling and removal of solids		
Media			
Materials	Washed, durable granular material		
Uniformity coefficient	Less than 4.0 between smallest and largest size particles		
Depth	24 to 36 in. (610 to 914 mm)		
Effective size	0.3 to 1 mm	0.3 to 1 mm	0.8 to 3 mm
Hydraulic loading	<1.5 gpd/ft^2 (<61 L/day m^2)	2 to 5 gpd/ft^2 (82 to 204 L/day m^2)	3 to 5 gpd/ft^2 [b] (122 to 204 L/day m^2)
Media temperature	>41°F (>5°C)	>41°F (>5°C)	>41°F (>5°C)
Dosing frequency	<2 per day	<2 per day	5–10 min./30 min.[d]
Recirculation ratio[c]	(Not applicable)	(Not applicable)	3:1 to 5:1

Source: National Small Flows Clearinghouse, *Pipeline*, Summer 1997, Vol. 8, No. 3.

[a]These values show typical design criteria and do not represent all possibilities.

[b]Forward flow only, not including recirculated effluent.

[c]Water recirculated: water discharged.

[d]Dosage lasts for 5 to 10 minutes every half hour.

(Fig. 19.3). They are nearly identical in performance to buried sand filters (Fig. 20.39)—the difference is that these are at least partially aboveground. A detail of the filter medium is shown in Fig. 20.40. Table 20.11 shows that they are able to accept a somewhat higher flow than a buried filter, thus requiring less area than the latter, but also leaving the surface no longer usable for any other purpose. (A removable cover is typically used for odor control, despite the "open" name.) They are used on systems with flows of up to 120,000 gpd (454,240 L/day) of wastewater. Frequently, two such open filters are built so that one can rest while the other is in use. Alternatively, two filters may be used in series, with an even cleaner resulting final effluent.

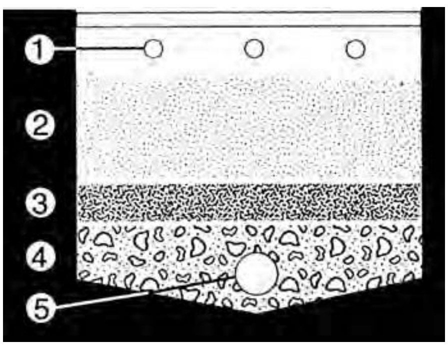


Fig. 20.40 *Open sand filter receives wastewater from above through (1) distribution pipes (or a thin layer of flooded wastewater). A filter medium (2) such as sand is on top, then (3) fine gravel, then (4) coarse gravel, surrounding the (5) underdrain. Slow sand filters are very similar. (National Small Flows Clearinghouse.)*

(b) Recirculating Sand Filters

These eliminate odors by ensuring an adequate supply of oxygen to the wastewater. The recirculating sand filter (Fig. 20.41) first receives water (from the septic tank or other primary treatment) into a recirculation tank. This tank has a pump, a timing mechanism, and float valves. Either in timed doses or when triggered by the float valve, doses of water are pumped to the sand filter. The treated wastewater collects in the underdrain, where the majority (75% to 80%) is directed back to the recirculation tank. Thus, mixing with the septic tank effluent and being pumped to the sand filter, the result is weaker (cleaner) effluent, containing more oxygen, entering the sand filter. This eliminates odor and allows for a slightly larger filter grain size, making the system less prone to clogging. Table 20.11 compares sand filter types, showing the highest allowable flow rates per surface area for the recirculating sand filter.

At Stonehurst, a 47-lot subdivision in Contra Costa County, California, 1500-gal (5680-L) septic tanks serve each unit; each tank has a screened

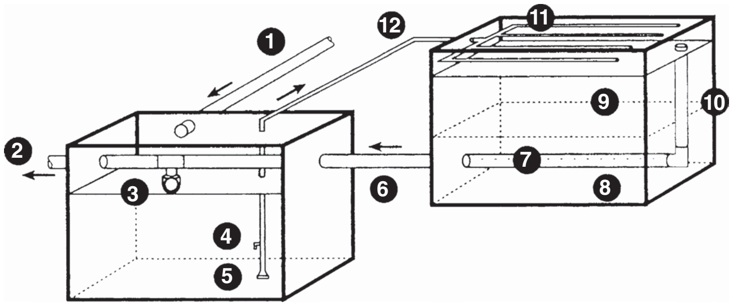


Fig. 20.41 *Recirculating sand filters periodically distribute a cleaner, more oxygen-rich effluent to the sand filter. This eliminates odor and allows a larger grain size for the medium. (1) Effluent from pretreatment (such as a septic tank). (2) To disinfection/discharge. (3) Float valve. (4) Bleed line. (5) Submersible pump. (6) Recirculated effluent line. (7) Perforated underdrain piping. (8) Layered support gravel. (9) Filter media. (10) Riser pipe. (11) Distribution piping. (12) Recirculation pump discharge to recirculating filter. (National Small Flows Clearinghouse.)*

effluent vault, keeping solids out of the effluent lines. The effluent is taken through small-diameter, variable-grade sewers (located under the roadway) to a recirculating granular medium filter. (Homes lower than the roadway use effluent pumps at the septic tank outflows.) Outflow from the recirculating filter is then taken to a UV recirculation tank, where it is treated by UV radiation (see Fig. 19.6). From this tertiary treatment area, it is passed to a subsurface drip irrigation system serving a community park. In winter, a 2.5-acre (1-hectare) community soil absorption field is utilized.

(c) Lagoons

These basins need sun, wind, and more land area than other methods, but are very simple to maintain and very low in energy use. They usually must be lined to prevent wastewater from polluting the groundwater. Sometimes the outflow must undergo further treatment before release. If lagoons are not square or round, their length should not exceed three times their width. Outflow and inflow should be at opposite ends. Detailed information is available from the National Small Flows Clearinghouse (1997).

Anaerobic lagoons are usually used as the first of at least two lagoons in series. Working much like a septic tank, they hold wastewater for 20 to 50 days and are relatively deep, 8 to 15 ft (2.4 to 4.6 m). With a surface of floating scum that blocks oxygen from the wastewater, they are unsightly and malodorous.

Aerobic lagoons are shallower than other lagoons, so sunlight and oxygen from wind and air can better penetrate. Aerobic bacteria and algae do the work of cleaning the wastewater. These are best in warm climates where freezing is not a threat. They hold water for 3 to 50 days. The bottoms are either paved or lined to prevent weeds from growing within the lagoon.

Aerated lagoons take the aerobic lagoon a step further, actively stirring and adding oxygen to the lagoon. Because they speed aerobic action, they require shorter retention time and less land area than a passive aerobic lagoon.

Facultative lagoons (also called *stabilization, oxidation, photosynthetic*, or *aerobic-anaerobic ponds*) are the type most commonly used by small communities and individual households. They work in most climates and require no machinery. They require about 1 acre (0.4 hectare) for every 50 homes (or for every 200 people) served, are 3 to 8 ft (0.9 to 2.4 m) deep, and are designed to hold wastewater for 20 to 150 days (the longer period in cold weather).

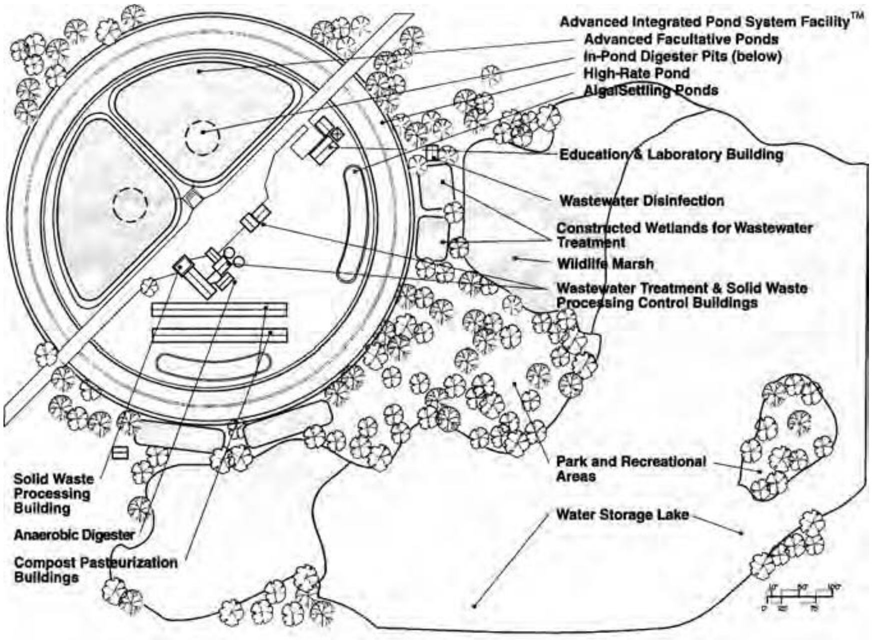
Three layers form in these lagoons: the top is an aerobic zone, the middle is the facultative zone, and at the bottom is the anaerobic zone. The depth of the surface aerobic zone depends upon how much sunlight, wind, and rain can contribute oxygen; the deeper this zone is, the better it controls odors rising from the anaerobic zone. Therefore, these lagoons should be sited with full access to both sun and wind.

Down in the anaerobic zone, anaerobic bacteria convert sludge to gases, including hydrogen sulfide, ammonia, and methane. As these gases rise, they provide food for both the aerobic bacteria and the algae in the aerobic zone. Sludge accumulates more quickly in cold climates; sludge removal should be expected every 5 to 10 years.

(d) Advanced Integrated Wastewater Pond System (AIWPS™)

At California Polytechnic State University, San Luis Obispo, there was an innovative proposal to create an integrated infrastructure facility combining campus wastewater treatment and solid waste processing. In addition to the waste treatment and resources recovery for this campus of 18,000, the schematic design for the Energy Efficient Resource Recovery (E2R2) Facility includes an educational facility, a wildlife habitat, and park facilities. The wastewater and related wetlands proposals are shown in Fig. 20.42; the solid waste facility appears in Fig. 21.1.

Three ponds are used in an AIWPS facility (Oswald, 1990; Oswald et al., 1963). The first is the advanced facultative pond (AFP; Fig. 20.42*a*), which includes an in-pond digester (IPD) or anaerobic fermentation pit at the bottom, and an oxygen-rich aerobic surface water layer. Two AFPs used in parallel allow fail-safe operation. This design



(a)

Fig. 20.42 *Schematic design proposal for wastewater treatment at the Energy Efficient Resource Recovery (E2R2) Facility at Cal Poly, San Luis Obispo. (a) Site plan. (b) Effluent enters the advanced facultative pond (AFP) through the in-pond digester, where solids settle, undergo methane fermentation, and are reduced to ash. Rising biogas is channeled by a proprietary submerged gas collector and passes through a highly aerobic surface layer where impurities are removed, yielding methane-rich biogas at the surface. (c) AFP effluent then goes to the high-rate pond, where it is slowly moved along the shallow channels by an energy-efficient paddle wheel providing optimum solar exposure and enabling the profusely growing algae to supply abundant oxygen for oxidation of wastewater organics and disinfection of pathogens. Subsequently, effluent moves into the quiescent Algal Settling Pond where algae settles and is periodically removed for beneficial use. (d) Effluent then moves into constructed wetlands, where the plants in this system create an ideal environment for invertebrates and vertebrates (in free surface wetlands) and aerobic and anaerobic microbial populations to thrive and provide further treatment and effluent polishing. Finally, the effluent from the wetlands is disinfected by ozone or UV disinfection systems and stored in a lake that is part of a campus park and recreational facility. (Courtesy of Dr. William Oswald, Professor Emeritus of Civil and Environmental Engineering and Public Health at the University of California, Berkeley, and Principal of Oswald Engineering Associates, Inc.; Dr. Bailey Green, Research Engineer at the University of California, Berkeley, and Principal of Oswald Engineering Associates, Inc.; and Professor Daniel Panetta, Architecture Department, Cal Poly, San Luis Obispo.)*

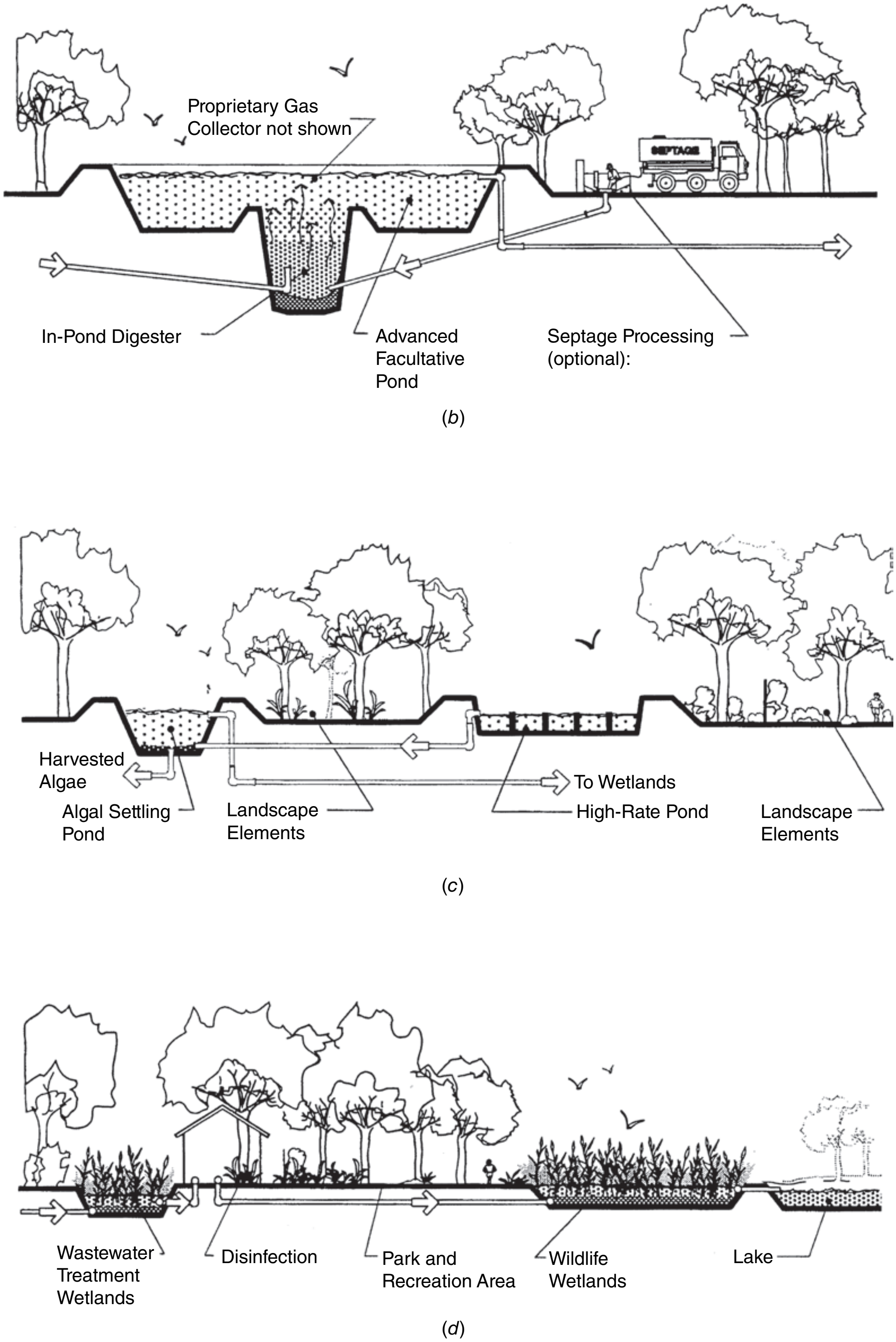


Fig. 20.42 *(Continued)*

enables isolation and treatment of toxic substances in the event that such material is accidentally released into the community sewer system. Conventional sewage treatment plants typically cannot isolate or treat accidental toxic releases in wastewater due to their short processing time.

The raw sewage enters the system near the bottom of the IPD, where anaerobic bacteria slowly reduce biosolids to ash (Oswald et al., 1994). Biochemical oxygen demand (BOD) is reduced to 60–80%, and minimal accumulation of refractory solids (sludge) has been demonstrated in installations since the late 1960s.

Using earthwork construction for the ponds allows them to be quite large and deep, without the substantially higher costs of concrete and steel construction typical of conventional wastewater treatment facilities. A berm surrounding the IPD prevents mixing of aerobic water with the influent below, whether by wind or thermal inversion. The aerobic upper layer oxidizes any malodorous biogases rising from the IPD. The biogas generated in the IPD is scrubbed as it passes through the water column and the aerobic surface layer. With a campus population of 18,000, between 3000 and 5000 ft^3 (85 and 142 m^3) per day of methane (CH_4) were estimated to be available for collection from the IPD and use as fuel (Green et al., 1995a).

The second pond is the high-rate pond (HRP) designed to grow algae (Fig. 20.42*b*). The lined channels in this pond are approximately 3 ft (1 m) or less in water depth and include a paddle wheel (see Fig. 20.49) to slowly mix the primary effluent. The HRP design allows maximum oxygen production by algal photosynthesis due to optimum exposure to sunlight and abundant nutrients. The pond's aerobic and facultative bacteria oxidize most of the soluble and readily biodegradable BOD.

The next pond in the series is an algal settling pond (ASP; Fig. 20.42*c*). The quiet waters of this pond allow 50% to 80% of the algae to settle over several days' residence time. The settled algae are periodically harvested, and the algal biomass does not produce objectionable odors. When properly disinfected, the harvested algae, rich in nitrogen and phosphorus, can be used as fish or livestock feed, or as a nitrogen source in compost.

Near St. Helena, California, an AIWPS facility has functioned since the late 1960s. During this time period, no sludge removal has been necessary, attesting to the efficacy of the methane fermentation process. The facility is near several large wineries and is considered a good neighbor without odor problems (Oswald et al., 1970).

While a maturation pond usually follows the ASP in an AIWPS facility, various appropriate treatment components can subsequently be used to achieve advanced tertiary treatment—the highest wastewater reclamation and reuse standard required by the state of California (Green et al., 1996). In the proposed Cal Poly design, the ASP effluent flows into a constructed wetland.

(e) Constructed Wetlands

Wetland surrogates constructed specifically for waste treatment are shown in Fig. 20.42*c*. In the schematic design, two parallel-constructed wetlands are proposed—allowing for a comparison between their outflows.

The free surface wetlands (FSW) consist of shallow open basins or channels that are lined to prevent seepage. Soil supports a succession of wetlands vegetation, nourished by a continuing flow of effluent from the initial wastewater treatment system(s) (such as a secondary AIWPS facility, septic tank, etc.). Although the water surface is exposed to beneficial air and sunlight, proper design is required to mitigate human contact with the treated effluent in FSWs. It is also necessary to address potential problems such as mosquitoes or other water-borne insects.

The subsurface flow wetlands utilize a lined treatment basin filled with a coarse medium such as large gravel or crushed rock. The large voids (if properly designed) allow the effluent to flow freely through rocks and plant root systems. The relationships among gravel size, slope of bed, and rate of flow is complex and is described in detail in an EPA document (EPA, 1993). A layer of soil is used to cover the gravel bed, so subsequent human contacts with the effluent and insect problems are precluded.

In either type of constructed wetland system, saturated and nutrient-rich conditions encourage the growth of both aerobic and anaerobic microbes and certain invertebrates. The most common plants include varieties of *scripus* (bulrushes), *phragmites* (reeds), *typha* (cattails), *canna*, and *iris*. These plants not only provide large amounts of surface area for microbial activities, but also create an aerobic zone underwater by transporting air through their stems to their roots. A thin aerobic environment results among the root hairs.

Constructed wetlands become a vivid, colorful demonstration of how, in nature, there is no such thing as waste. After passage through a slow sand filter (see again Fig. 19.3) and final disinfection, the reclaimed water from the E2R2 facility can provide campus landscape irrigation water, be released into the campus creek to assist with habitat restoration, or be used for aquifer recharge. Arcata, California, completed its wetlands treatment system in 1986. This system draws several hundred species of birds, as its abundant vegetation removes nutrients from, and allows habitat reuse of, the city's treated wastewater.

(f) Greenhouse Ecosystems

When constructed wetlands are moved indoors, greater control and less required area become possible. As pioneered by marine biologist John Todd at Ocean Arks International, *Living Machines* are a series of tanks, each with a particular ecosystem, that form a "stream." The stream is followed by an indoor marsh; together they achieve a high degree of tertiary wastewater treatment.

These enclosed systems typically cost less to construct and about the same to maintain as conventional sewage treatment plants, but use less energy because photosynthesis (solar energy) and gravity flow largely replace energy-intensive pumps and large-scale aerators. These systems do not harm the environment with a final dose of chlorine, and they produce about one-quarter of the sludge of conventional systems. Because they are pleasant to look at and smell much like commercial greenhouses, they can be located within the neighborhoods they serve. This can save the huge costs associated with large-diameter, deep-trench sewer lines and pumping stations necessary with distant, centralized treatment plants.

A diagram of one greenhouse ecosystem is shown in Fig. 20.43. This Living Machine begins with an anaerobic bioreactor, in effect a septic tank where solids are reduced to sludge and methane gas is produced. From here the wastewater passes to aerated tanks, and then to *ecological fluidized beds*, each with a particular combination of bacteria, algae, snails, and fish. The further along the treatment process, the more advanced the ecosystem, with goldfish (carp) growing in the final clarifier. This process depends upon the following food chain: (1) aerobic bacteria consume suspended organic matter and convert ammonia into nitrites and then nitrates; (2) algae and duckweed feed on the products of the bacterial action; (3) snails and zooplankton eat the algae, while floating duckweed provides shade that discourages algal growth in the later stages of the process; (4) fish eat the zooplankton and the snails. Plants range from water hyacinth in the early stages to an increasing variety of specialized "accumulators" that remove troublesome phosphorus, heavy metals, and so on. Papyrus, canna lilies, bald cypress, willows, and eucalyptus (among other plants) all have a role. When trees outgrow the greenhouse, they are transplanted outdoors. It should be kept in mind that said trees are long-term storage devices for the heavy metals they absorb, not final solutions, because heavy metals will be returned to the earth when the trees die and decompose. Plants can be sold to nurseries or ground up as compost; the fish also enrich the compost. The smaller fish (shiners) can be sold as bait fish. These are small enough to dart back and forth in the piping between tanks, choosing their water quality. If a toxic slug of waste enters the system, they swim to later, clearer tanks until the danger is past.

The greenhouse solar aquatic system in Fig. 20.44*a* cleans the wastewater from a mobile home park on Vancouver Island, British Columbia. In Fig. 20.44*b*, a striking Living Machine design occupies the center of an urban block in Kolding, Denmark.

In milder climates and with specialized wastewater, these processes can be achieved without the greenhouse enclosure. The Sonoma Mountain Brewery's Living Machine (Fig. 20.45) near Sonoma, California, occupies about 1 acre (0.4 hectare) and treats a maximum flow of 7800 gpd (29,525 L/day) of waste from the brewery process. Two streams move in parallel, allowing a comparison of their outflows as experiments

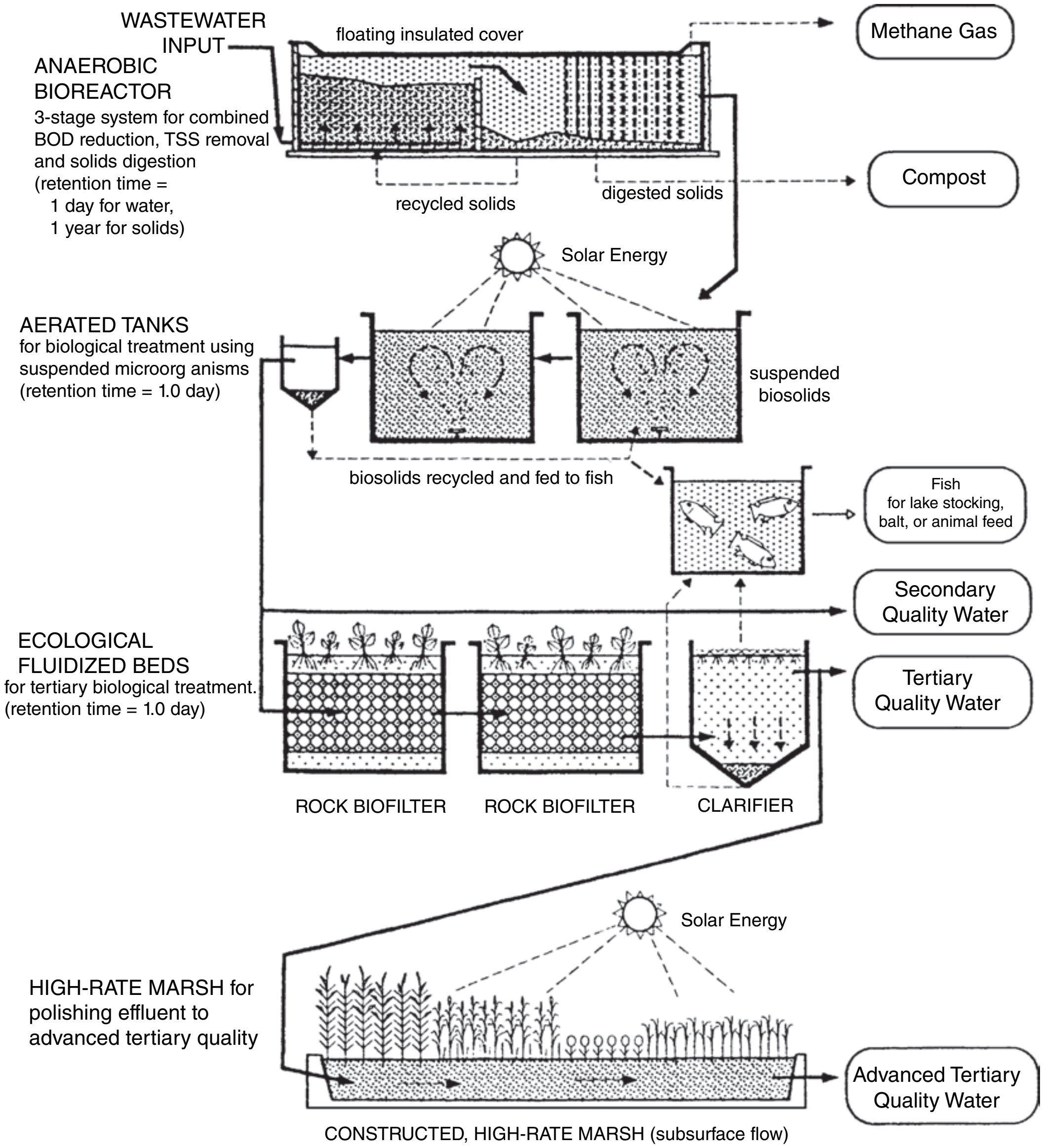


Fig. 20.43 *A Living Machine enclosed within a greenhouse uses a food chain in a series of ecosystems to treat wastewater. (Living Technologies, Inc.)*

(a)

(b)

Fig. 20.44 *(a) A greenhouse in a mobile home park in British Columbia encloses the 12 solar tanks and marsh of a Solar Aquatics System, designed by Ecological Engineering Associates and ECO-TEK, Inc. (Photo by Charles Rusch.) (b) In the middle of an urban block in Denmark, a Living Machine is a good neighbor. (Photo © 1996 by Robert Peña.)*

(a)

(b)

Fig. 20.45 *In the mild climate of California's Sonoma Valley, the waste from the Sonoma Mountain Brewery (a) is treated by an outdoor Living Machine (b). Flow is from left tanks to right tanks, then to a marsh. (c) Calla lilies and other plants lend beauty as well as function to this open aerobic tank. (Designed by Living Technologies, Burlington, VT.)*

(c)

with detailed ecosystems are conducted. A part-time operator manages this treatment plant. After an underground anaerobic holding tank, flow moves to:

1. Closed aerobic reactors, each holding 2500 gal (9463 L). Air is blown through the tanks from the bottom (an adjacent small building encloses the blower); wastewater spends about 15 hours in these tanks. Next are—
2. Open aerobic tanks, four per stream. Plants, snails, and organisms can migrate among the agitated tanks, choosing their preferred level of nutrients ("pollution"). Water leaving the last of these tanks is much cleaner; water and sludge collected from the tanks are taken next to the—
3. Clarifier. Shaded by water hyacinth, algae cannot grow in the water at this advanced stage. In this quiet-water environment, solids settle out and are then pumped to an adjacent—
4. Open-air reed bed ("composter"), where they are dried and then composted. The compost will serve as nutrient for the hops used in the brewing process. Excess water percolates through an underlying sand bed and is returned to the beginning of the Living Machine streams. Meanwhile the clarified water passes next to—
5. Ecological fluidized beds (two per stream), whose purpose is to further polish the wastewater. Water circulates many times through this section, pumped from the plant-shaded perimeter into a rock bed at the center. In this bed, microorganisms continue to clean the water. From the second ecological fluidized bed, water moves to an underground—
6. Irrigation pond, from where it is filtered through a—
7. Constructed wetland for further purification.

Finally, it is welcomed for irrigation of the hops and grapevines grown on site.

The IslandWood environmental education campus on Bainbridge Island, Washington, prominently features a Living Machine (Fig. 20.46) as a focal point near a major classroom. This location brings waste processing into the consciousness of those using the campus and reminds viewers that human wastes do not literally just disappear if piped off site. In this cool climate setting, the greenhouse provides a thermal environment to support the biological waste treatment processes that are the heart of a Living Machine.

(g) Pasveer Oxidation Stream

This method of sewage treatment (Figs. 20.47 and 20.48) has been adopted at the New York Institute of Technology. Serving the 450-acre (182-hectare) campus at Old Westbury, Long Island, New York, this system provides on-campus sewage treatment, which returns purified effluent to the ground through 48 leaching wells located under the athletic field. The groundwater, thus restored, provides a contributing source of water for 400-ft (122-m) deep wells, distantly located, that furnish part of the water supply for the campus buildings (see Fig. 20.47).

A few of the original small buildings, later converted to administration offices and classrooms, are still served by septic tanks and leaching fields. There was no public sewer near the campus, and in the 1970s the health authorities ruled out the use of septic tanks for the numerous additional buildings that were being contemplated.

The oxidation stream process applied here was developed by the Netherlands Research Institute for Public Health Engineering, and is now in operation in many U.S. locations as well as in Europe. It is considered to be a modified form of the *activated sludge* process (see later discussion of the Oceanside Plant in Section 20.8*b*) composed of aerobic digestion and periodic sludge removal.

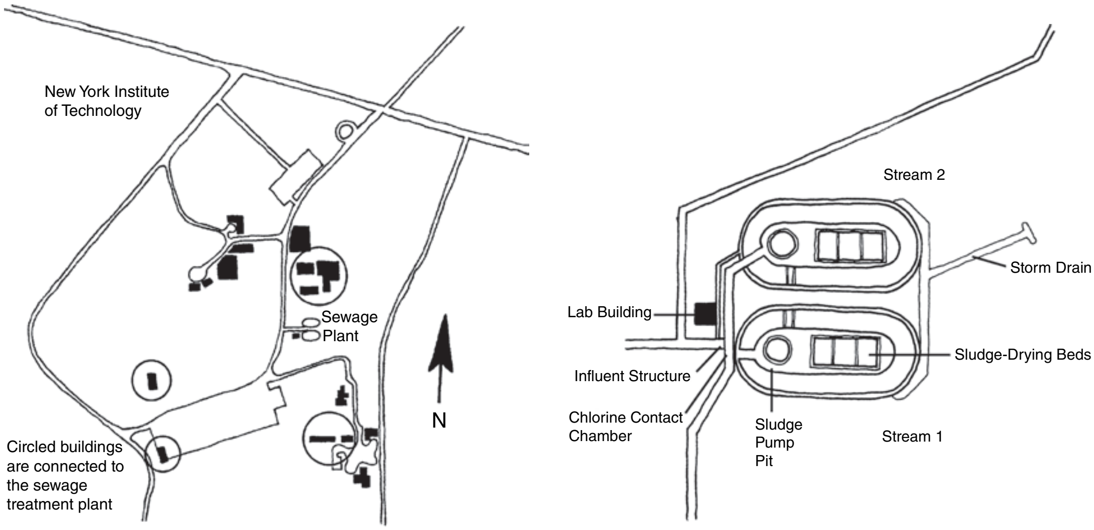
The mechanical aerator (Fig. 20.48) which keeps the stream of sewage moving, while providing the oxidation necessary for aerobic digestion, is an important feature. In this design, sludge-drying beds are placed on an island, surrounded by the continuously moving oxidation stream. Another feature of the system is its low profile (Fig. 20.49), readily screened by trees. The aerobic digestion process is not malodorous. Sound is produced by the splashing water-wheel action of the mechanical aerators; no air compressor is required (reducing noise generation).

The plant has a full-time accredited operator; there are also two assistants and one relief operator. This design provides for an eventual population of 4330, with a 340,000-gpd (1,287,010-L/day) flow. Sludge was removed from the drying beds twice in the first five years of operation.

(*a*)

(*b*)

Fig. 20.46 *(a) Greenhouse enclosing a Living Machine on the IslandWood campus on Bainbridge Island, Washington. (b) Interior view of the IslandWood Living Machine, showing plant materials that are an integral aspect of this biological waste treatment approach. (© Alison Kwok; all rights reserved.)*



(*a*) (*b*)

Fig. 20.47 *Sewage treatment plant, New York Institute of Technology (NYIT). (a) The treatment plant's location is central to all of the buildings it serves—an efficient choice. (b) Layout of the treatment plant. Because of the plant's odorless operation, its proximity to campus buildings poses no problem. (Courtesy of Bogen Jenal, Engineers, P.C. Redrawn by Amanda Clegg.)*

(*a*) (*b*)

Fig. 20.48 *Details of NYIT treatment plant. (a) Rotor with a plastic "greenhouse" cover. (b) The rotor induces oxidation in this oval circulating stream. (A similar mechanism serves the high-rate pond in Fig. 20.41.)*

(*a*)

(*b*)

Fig. 20.49 *NYIT sewage treatment plant at completion. (a) The only projections above ground level are the office/laboratory and the plastic covers over the rotors. (b) The oxidation stream does not appear turbulent here, but it becomes so under the action of the mechanical aerator (rotor).*

20.8 LARGER-SCALE SEWAGE TREATMENT SYSTEMS

Two examples of community-wide sewage treatment are presented here—one for a small, water-scarce community near San Diego, California, and one for an oceanside urban neighborhood in San Francisco.

(a) Padre Dam Municipal Water District

The Santee Water Reclamation Plant (Fig. 20.50) incorporates innovations in water conservation and recycling developed during the 1960s and 1970s. The Padre Dam Municipal Water District is a region where rainfall is less than 15 in. (380 mm) per year. It has no local water supplies, so water is imported 300 miles (480 km) from the Colorado River. If conventionally treated, the wastewater resulting from water usage would be discharged into the Pacific Ocean. Alternative sewage treatment (shown here) processes this fluid waste for secondary uses such as irrigation and recharging of groundwater. Many municipal potable water supplies are taken from rivers often heavily polluted with sewage. After treatment, water from such sources is pumped into domestic water supply mains. Therefore, district officials here decided to install a system that would make use of purified wastewater for many secondary uses.

However, would such a concept be acceptable to the public? An effective public relations program concurrent with the incorporated technological advances has proved successful.

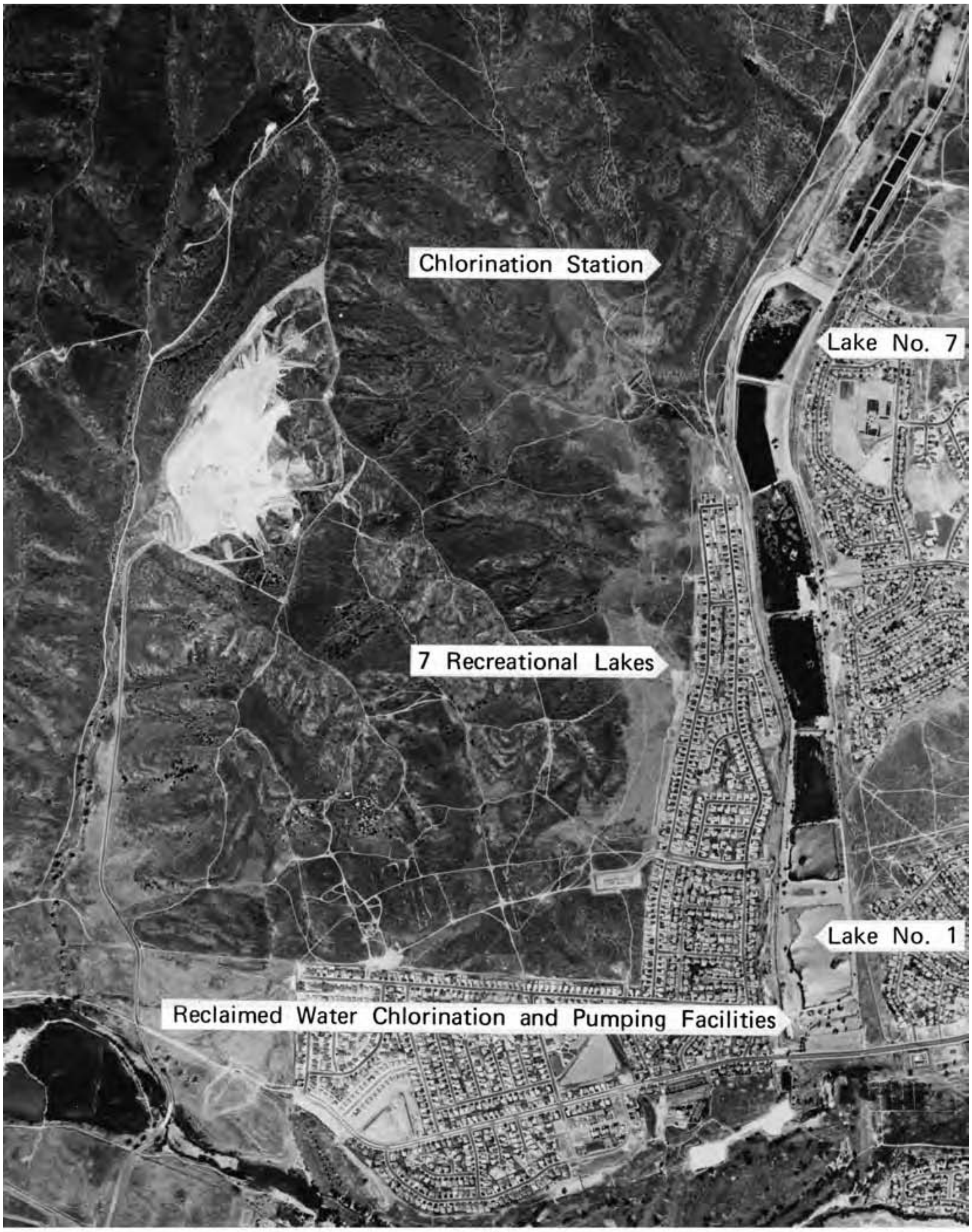
The project involved building a sewage treatment plant and utilizing seven pits left over from prior surface mining of sand and gravel. After partial purification of the sewage at the plant through the first two stages of a conventional activated sludge process, the effluent is discharged to form the lakes adjacent to the plant. This provides tertiary (oxidation) treatment, after which the cleaner effluent is pumped to a filter area at the north end of the complex, where it is further purified through sand and gravel. Chlorination is performed, and the water then flows through a series of seven lakes, Nos. 7–6–5–4–3–2–1, in that order.

The appearance of new lakes in this semiarid region created initial interest that was rapidly augmented by a very clever program. At first, the lakes were fenced in. Then the fences were removed. Next, the seven lakes were made available for boating. They were stocked with fish, and careful studies were made that indicated that the fish were healthy and flourishing. Fishing was permitted, but for a while, all fish had to be returned to the water. Anglers were later permitted to keep and consume the fish. Finally, swimming was permitted. The overflow from the last lake, No. 1, discharges into Sycamore Canyon Creek and is used for irrigation of a golf course and the recharging of groundwater.

(b) Oceanside Water Pollution Control Plant

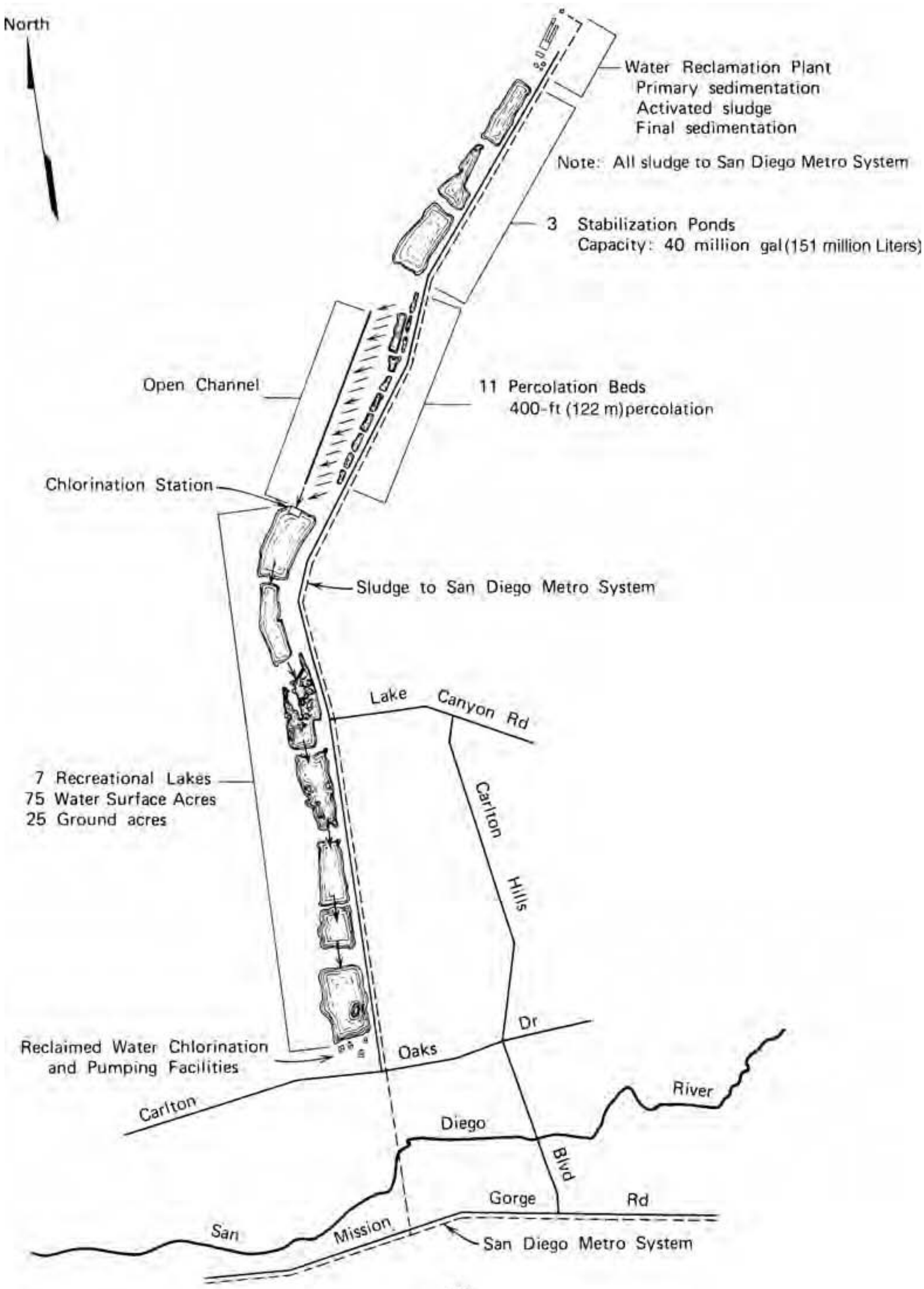
Imagine the challenge of locating a major new sewage treatment plant on the shore of the Pacific Ocean, within the city of San Francisco, immediately adjacent to both the city zoo and a well-established neighborhood. This plant treats all the sewage in the western San Francisco watershed, an average dry-weather flow of 21 million gal/day (79,491,720 L/day). The treated effluent is discharged through an ocean-bottom pipeline, 4.5 miles (7.2 km) offshore, with effluent and ocean water quality monitored by an on-site laboratory. Sludge is shipped north to serve as the required daily cover for a landfill near Novato. The plant itself is concealed by large earth berms, through which entry and exit tunnels carry plant traffic. And the odor? It is completely contained within a huge underground complex of wastewater basins and channels, over which the zoo proposed to build a Mammal Conservation Center on 5 ft (1.5 m) of topsoil cover. Exhaust air from the underground plant is filtered through activated carbon and potassium permanganate before release.

The process is shown in simplified form in Fig. 20.51*a*. Incoming sewage passes through a bar screen and grit chambers, which remove the largest objects as well as grit, sand, and gravel (these are trucked to a landfill). Then the water flows to the primary clarifier, in which floating scum is skimmed off, and sludge settling on the bottom is pumped to the egg-shaped anaerobic digesters (Fig. 20.51*b*). The wastewater flows next to aeration tanks where bacteria grow fat, feeding on and breaking down the remaining dissolved and suspended solids. Next is the secondary clarifier, where the fattened bacteria (activated sludge) sink to the bottom. Part of this activated sludge is returned to the aeration tanks to bolster the bacterial culture there. The remainder is thickened and pumped to the digesters.



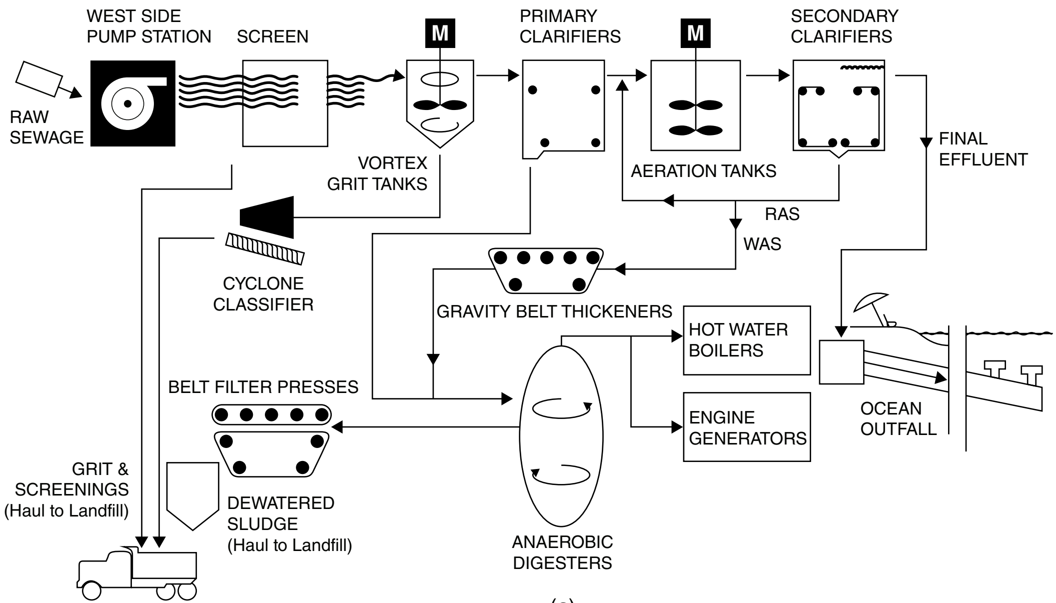
(a)

Fig. 20.50 *Santee Water Reclamation Plant and Santee Park and Recreational Facilities, Padre Dam Municipal Water District, California. (a) Aerial photograph of the Santee Plant, including the seven recreational lakes. Note the location of the San Diego River at the bottom of the photograph. The water reclamation plant and the stabilization ponds do not appear in this aerial view. (b) Raw sewage from the community of Santee enters the treatment plant, which is located at the top of this diagram. The process then proceeds south to the point where reclaimed water is pumped to irrigation or recharges groundwater. Sludge is pumped to the San Diego Metro system. The plant is not burdened by storm water, which is recharged to the ground locally in the community.*

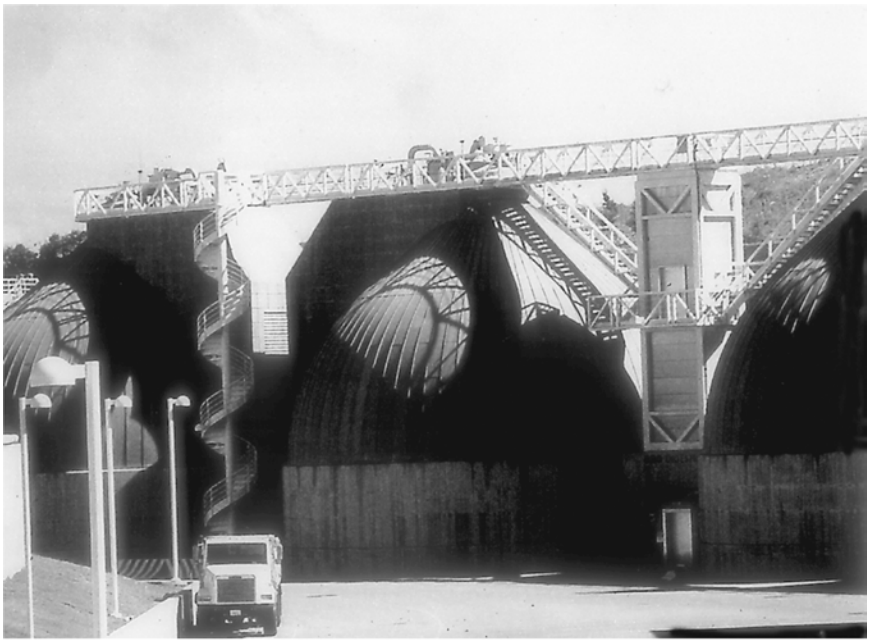


(b)

Fig. 20.50 *(Continued)*



(*a*)



(*b*)

Fig. 20.51 *The Oceanside Water Pollution Control Plant, San Francisco, is largely underground, as well as hidden behind high earth berms. (a) Flow diagram. (Courtesy CH2M Hill and the City/County of San Francisco.) (b) View of some of the egg-shaped anaerobic digesters from within the berm walls. Biogas produced within the four 750,000-gal (28,375-m^3) digesters supplies about 20% of the electricity used in the treatment plant.*

Thus, the anaerobic digesters receive both primary sludge and thickened, activated sludge. As this sludge is stabilized and reduced in volume, biogas is produced: enough to heat water for both process and facility heating, and to generate about one-fifth of the electricity used within the plant. Sludge leaving the digesters is dewatered in belt presses, before being hauled to the landfill. During summer, biosolids are spread on agricultural land for soil enrichment.

Questions remain about such use of biosolids. Although a 1998 EPA national survey of sewage sludge found toxic chemicals at such low levels that regulation was deemed unnecessary, concentrations of certain industries may produce local chemical or radioactive sludge pollutants at higher levels. Intercepting such wastes at their source, rather than allowing them into the sewage stream, seems an obvious imperative.

20.9 RECYCLING AND GRAYWATER

These chapters on water and waste have illustrated four common "grades" of water in buildings:

Potable water (usually treated, suitable for drinking)

Rainwater

Graywater (wastewater not from toilets or urinals)

Blackwater (water containing toilet or urinal waste)

Two more categories are:

Dark graywater (from washing machines with dirty diaper loads, kitchen sinks, and dishwashers; usually prohibited for reuse)

Clearwater (backwash water from reverse osmosis water treatment; condensation from a cooling coil)

After considering the many blackwater sewage treatment complications described in the previous section, it might be expected that graywater reuse would, by contrast, be a simple matter. However, there are lingering prejudices against wastewater of any kind that complicate, or directly prohibit, such water recycling. This section presents some future approaches that may be more actively implemented if water conservation is to be taken seriously, followed by some code-mandated approaches.

Rainwater, given an adequate supply, could meet the need for many uses of water in and around a building: bathing and laundry, toilet flushing, irrigation, and evaporative cooling, for example. Little or no treatment of rainwater is needed for such uses.

Blackwater requires much more extensive treatment, given its high concentration of human waste. However, this may be the easiest waste stream to eliminate, given the several waterless alternatives discussed in Section 20.1.

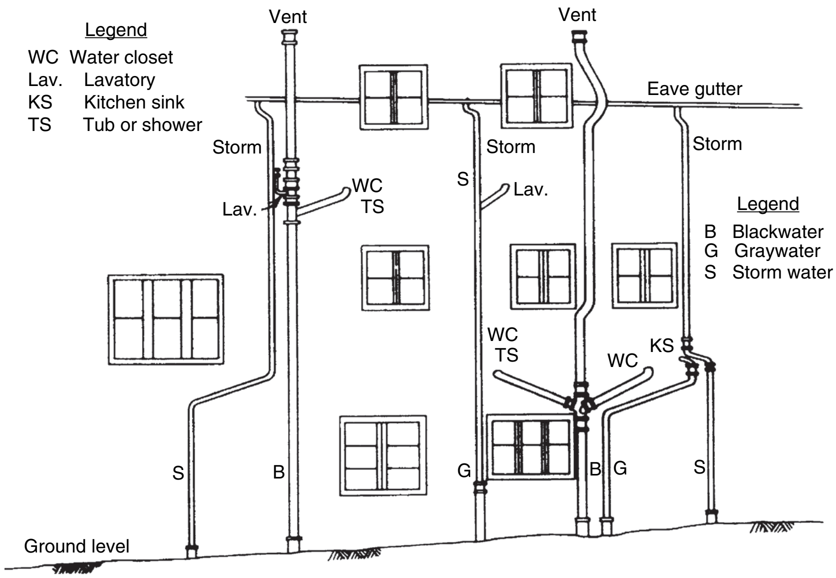
Graywater (also spelled *greywater*) reuse opportunities are more limited than those of rainwater, because graywater carries increased threats from pathogens. It must undergo treatment before reuse in toilet flushing. It is likely to contain soap, hair, and, occasionally, human waste (from soiled clothes in the laundry). If it is to be used in drip irrigation systems, filtering is essential. If kitchen wastes are included, grease and food solids add to the problems. Graywater may well be dirtier than rainwater, but its supply is likely far more predictable and constant. However, codes tend to limit the use of graywater to underground landscape irrigation for single-family houses.

The collection of these separate types of water poses a problem. In the early years of indoor plumbing, rainwater, graywater, and blackwater were mixed together, which severely overloaded sewage treatment facilities in rainy weather. Today, graywater and blackwater are typically mixed, with rainwater being kept separate. There are precedents for keeping all three separate, however (Fig. 20.52).

(a) Graywater and Future Recycling

Notwithstanding present code restrictions, the potential for residential graywater reuse (given separate waste collection systems) was shown earlier (Fig. 20.1*b*). The 21 g/cd (gallons per capita per day; [80 L/cd]) produced by bathing can meet much of the 32 g/cd (120 L/cd) water consumption of a conventional water closet and all of the water needs of a low-flush water closet. The 14 g/cd (53 L/cd) produced by doing laundry can help with irrigation; limiting contact between irrigation water and people seems prudent, hence the previous emphasis on underground distribution. Table 20.12 relates both the quantity and quality of residential graywater to its use in irrigation. Another potential benefit of separate graywater collection is that the heat content of the water might be partially reclaimed

(a)



(b)

Fig. 20.52 *Residence of the 27th Vicar of the Parish Church at Bibury (established A.D. 1086) in the English Cotswolds. (a) Clearly, the plumbing was added after the construction of the residence—perhaps several hundred years later. In England the drainage system for an older building often appears on the outside of the building. (b) It seemed inappropriate to ask the vicar's permission to inspect his indoor facilities, so probable uses have been assigned. Note that (1) offsets of the vertical piping are made with "easy bends" and are pitched down in the direction of the flow; (2) vents are located at high outdoor points; and (3) stacks carrying blackwater (from toilets) are of larger pipe size than those carrying graywater. In this sparsely settled region of the Cotswolds, the dispersal of storm water to the ground and the private septic tank treatment of blackwater plus graywater can be satisfactory. (Photo by William McGuinness.)*

TABLE 20.12 Residential Graywater Sources for Irrigation

PART A. SOURCES WITH PUMPS		
Source	**Average Outflow Water Quantity**	**Outflow Water Relative Quality**
Clothes washing machine	30–50 gal (114–190 L) per load, top loader, 10 gal (38 L) per load, front loader. Average 1.5 loads per week per adult, 2.5 loads per week per child	Good: medium concentration of soaps, lint. With biocompatible cleaners, quality can improve to excellent; diapers degrade quality to poor.
Automatic dishwasher	5–10 gal (19–38 L) per load	Poor: low to high quantity of solids depending on degree of pre-rinsing; high salt and pH from conventional cleaning compounds
PART B. GRAVITY FLOW SOURCES		
Source	**Outflow Water Quantity**	**Outflow Water Quality**
Shower	20 gal (76 L) per day per person, low-flow	Excellent: minimal concentration of soap and shampoo, but hair can clog distribution pumps and lines
	40 gal (151 L) per day per person, high-flow	
Tub	40 gal (151 L) per bath	Concentration in tub water likely less than shower water
Bathroom lavatory	1–5 gal (4–19 L) per day per person	Good: concentration of soap, shaving cream, and toothpaste can be high
Kitchen sink	5–15 gal (19–57 L) per day per person	Mixed: high in nutrients but also high in solids, grease, and soap
Reverse-osmosis water purifier	3–5 gal per gallon of drinking water (3–5 L per L)	Excellent: usually no suspended solids; contains 25% more concentration of the same dissolved solids as tap water
Water softener backwash	5% of indoor water use	Very bad: extremely high in salt
Softened water	(All graywater from softened water source)	Poor: contains salt (unless potassium chloride is used in softening process)

Source: Adapted from *Create an Oasis with Greywater*, by Art Ludwig, © 1997, Art Ludwig. Poor Richard's Press, Santa Maria, CA.

(Table 20.13). In England, the Aquasaver Company diverts and cleans water from lavatories, baths, and showers for reuse in toilet flushing, clothes washing, car washing, and irrigation. This low-pressure system, installed behind panels in a bathroom, uses a pump to push graywater through a series of filters to remove soap, detergents, and other impurities and then to a storage tank (in the attic or above points of use). Here it undergoes weir and trickle filtration and then treatment with nonhazardous cleaning agents. Finally, before reuse, it passes through a carbon filter network.

Storage raises a health issue. To avoid bacteria buildup in graywater, storage should be avoided and the filtered water taken directly to irrigation. However, storage allows for controlled dosage, allows

TABLE 20.13 Heat Recovery from Graywater

Source	Volume/Use, gal (L)	Flow Rate, gal (L)	°F	°C	Quality	Coincident[a]
Kitchen sink	Up to 5 (up to 20)	2.5 (10)/min	85	30	Poor	No
Lavatory	Up to 1.5 (up to 5)	1.25 (5)/min	85	30	Fair	No
Bath	32 (120)	5 (20)/min	100	37	Good	No
Shower	15 (50)	2 (7)/min	100	37	Good	Yes
Washer	40 (150)	7 (25)/min	60	15	Moot	No

Source: Glenn Nelson, "Graywater Heat Recovery," © *Solar Age*, August 1981. Reprinted by permission.

[a]Coincident flow of warm wastewater and input water to heater. If "no," a holding tank is needed for heat exchange. If "yes," a countercurrent heat exchanger can be built into the drain line (see Fig. 20.53).

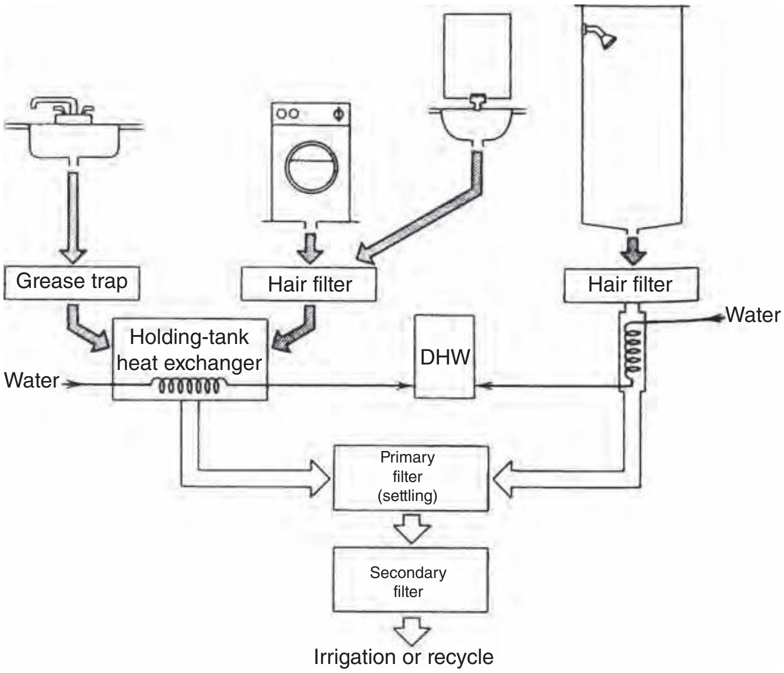


Fig. 20.53 *Sequence of water treatment and heat reclamation for domestic graywater, where such systems might be approved.*

solids to settle, allows for some potential heat recovery, provides for overflow to the sewer, and is often mandated by code.

Various stages of treatment are appropriate for different kinds of graywater (Fig. 20.53). Kitchen sink waste contains grease, which should be trapped (and periodically removed) before it can clog the filters and heat exchangers in a graywater recycling system. Similarly, lavatory showers and laundry waste contain lint and hair that must be intercepted quickly. Devices that do so (called *interceptors*) were described in Fig. 20.21.

Currently, many building codes tend to sharply limit graywater recycling, generally presume there will be no filtering, and rigidly constrict its use. It is hoped that such restrictions will loosen, with due regard for human health, as conservation of resources becomes more of an imperative than it already is. Adopters of the Living Building Challenge have worked to change (and challenge) graywater policies in cities in order to put in graywater systems.

An elegant and simple use of recovering energy from shower graywater (Fig. 20.54) is used in a residence built to Passive House criteria in Salem, Oregon.

Fig. 20.54 *Coils of copper tubing wrap a drainage pipe to form a heat exchanger to recover heat energy from the warm water in the shower above in a Passive House in Salem, Oregon. (© Bilyeu Homes; used with permission.)*

(b) Subsurface Irrigation

The 1997 *Uniform Building Code* (Appendix G), notes that water *only from* bathroom lavatories, showers, and tubs, and clothes-washing machines and laundry tubs, and *only in* single-family residences, can *only be used for* subsurface "irrigation" on the same site as the residence. The associated use of mandated trench constructions, as a means of avoiding any surface graywater distribution, may deliver very little water to plants.

Site conditions must meet the requirements of Table 20.14 and Figure 20.55. The bottom of the trenches must be at least 5 feet (1.5 m) *above* the highest known seasonal groundwater. Flow estimates are as follows:

Number of occupants:
- two for the first bedroom
- one for each additional bedroom

Combined showers, bathtubs, and washbasins, flow per occupant: 25 gal/day (95 L/day)

Laundry, flow per occupant: 15 gal/day (57 L/day)

A holding tank is required with a minimum 50-gal (189-L) capacity. An unvalved overflow must connect to the building sewer (ahead of any septic tank).

The irrigation/disposal field must be divided into a minimum of three valved zones (allowing the occupants to better direct flow rates). The total area of this field is the aggregate length of the perforated pipe times the width of the proposed field. The required area is based on the estimated graywater flow (or size of the holding tank, whichever is larger), the soil types and acceptance rates, as well as the trench design guidelines, shown in Table 20.15. If percolation tests are performed, the 24-hour percolation rate results must be within these limits:

Minimum, 0.83 gal/ft^2 (33.8 L/m^2)

Maximum, 5.12 gal/ft^2 (208.5 L/m^2)

One of several graywater system types is shown in Figure 20.56.

TABLE 20.14 Location of Residential Graywater System

	Minimum Clear Horizontal Distance Required			
	To Holding Tank		To Irrigation/Disposal Field[a]	
From	ft	m	ft	m
Building structures[b]	5[c]	1.524	2[d]	0.61
Property line adjoining private property	5	1.524	5	1.524
Water supply wells[e]	50	15.24	100	30.48
Streams and lakes[e]	50	15.24	50[f]	15.24
Sewage pits or cesspools	5	1.524	5	1.524
Disposal field and 100% expansion area	5	1.524	4[g]	1.219
Septic tank	0	0	5	1.524
On-site domestic water service line	5	1.524	5	1.524
Pressurized public water main	10	3.048	10[h]	3.048

Source: ©2012 *Uniform Plumbing Code*. Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

Note: SI units converted from mm to m by authors of this book.

[a]When irrigation/disposal fields are installed in sloping ground, the minimum horizontal distance between any part of the distribution system and the ground surface shall be fifteen (15) feet (4.6 m).

[b]Including porches and steps, whether covered or uncovered, breezeways, roofed porte-cocheres, roofed patios, carports, covered walks, covered driveways, and similar structures or appurtenances.

[c]The distance may be reduced to zero feet [meters] for above ground tanks when first approved by the Administrative Authority.

[d]Assumes a 45° (0.79 rad) angle from the foundation.

[e]Where special hazards are involved, the distance required shall be increased as may be directed by the Administrative Authority.

[f]These minimum clear horizontal distances shall also apply between the irrigation/disposal field and the ocean mean higher tide line.

[g]Plus two (2) feet (610 mm) for each additional foot of depth in excess of one (1) foot (305 mm) below the bottom of the drain line.

[h]For parallel construction. For crossings, approval by the Administrative Authority shall be required.

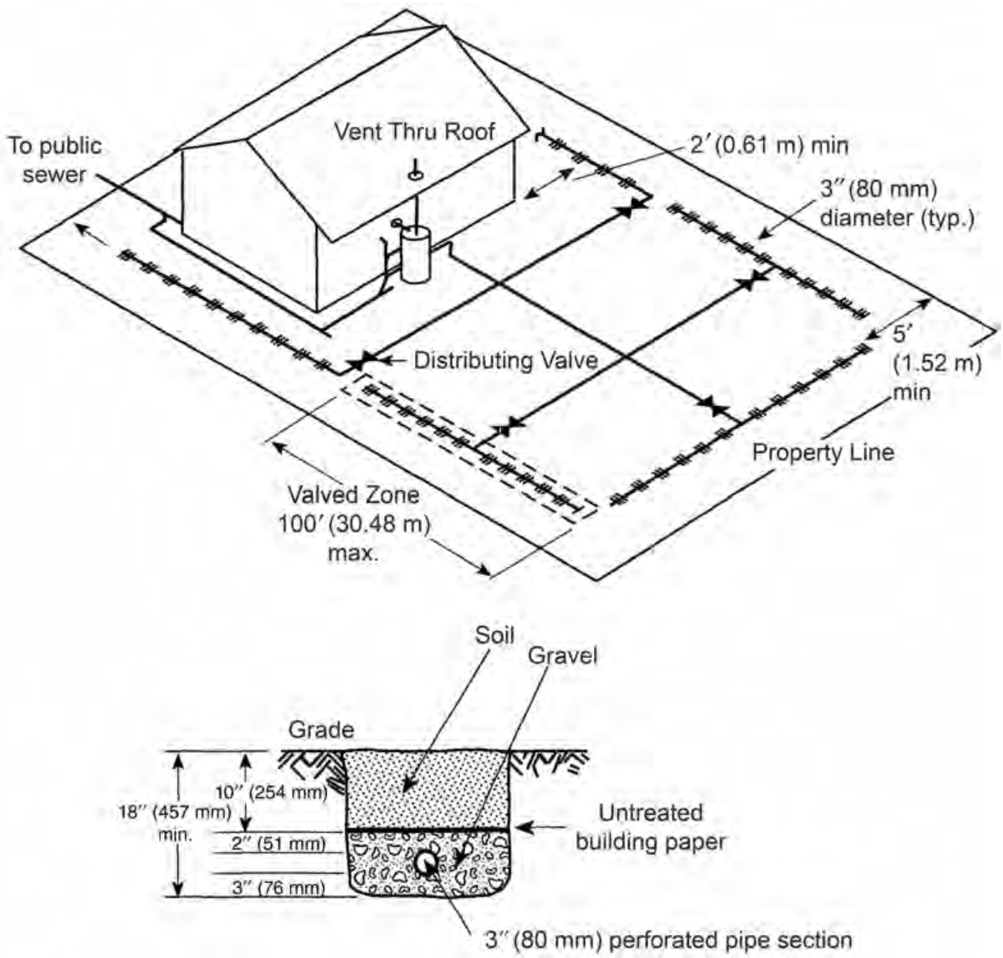


Fig. 20.55 *Example of a residence whose daily graywater flow requires an irrigation/disposal field (using a valved zone as shown in the detail). In this example, five such valved zones are shown (a minimum of three such zones are required). (©2006* Uniform Plumbing Code. *Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.)*

EXAMPLE 20.4 A four-bedroom single-family residence is located on sandy clay soil more than 5 ft (1.5 m) above the highest seasonal groundwater level. If the bathroom and laundry facilities contribute to a graywater system, how large an irrigation/disposal field is required?

SOLUTION

The total number of occupants = 2 + 1 + 1 + 1 = 5. Estimated graywater flow is

(25 + 15) gal/day per occupant × 5 occupants = 200 gal/day

[(95 + 57) L/day per occupant × 5 occupants = 760 L/day

Required field size (Table 20.15) of each valved zone is

$$60\ \text{ft}^2/100\ \text{gal} \times 200\ \text{gal/day} = 120\ \text{ft}^2$$

$$(1.5\ \text{m}^2/100\ \text{L} \times 760\ \text{L/day} = 11.4\ \text{m}^2)$$

If each valved zone has two lines at the minimum spacing of 4 ft (1.2 m), the minimum width of the irrigation/disposal field is 4 ft (1.2 m); the minimum length of the two perforated lines is therefore

$$120\ \text{ft}^2/4\ \text{ft} = 30\ \text{ft}$$

$$(11.4\ \text{m}^2/1.2\ \text{m} = 9.5\ \text{m})$$

Thus, three irrigation/disposal fields, each 4 ft by 30 ft (1.2 by 9.5 m), in trenches constructed as shown in Fig. 20.55, will meet code minimums. ■

TABLE 20.15 Graywater Design Criteria, Six Typical Soils

PART A. AREA OF IRRIGATION/LEACHING FIELD				
	Minimum Area of Irrigation/Leaching per Estimated Graywater Discharge per Day		***Maximum Absorption Capacity of Irrigation/Leaching per 24-Hour Period***	
Type of Soil	**ft²/100 gal**	**m²/L**	**gal/ft²**	**L/m²**
Coarse sand or gravel	20	0.005	5	203.7
Fine sand	25	0.006	4	162.9
Sandy loam	40	0.010	2.5	101.8
Sandy clay	60	0.015	1.7	69.2
Clay with considerable sand or gravel	90	0.022	1.1	44.8
Clay with small amounts of sand or gravel	120	0.030	0.8	32.6
PART B. IRRIGATION/LEACHING FIELD CONSTRUCTION				
	Minimum		***Maximum***	
	I-P	**SI**	**I-P**	**SI**
Number of valved zones	3	3		
Number of lines per valved zone	1	1		
Length of each perforated line			100 ft	30,840 mm
Bottom width of trench	12 in.	305 mm	18 in	457 mm
Spacing of lines, center-to-center	4 ft	1219 mm		
Depth of earth cover of lines	10 in.	254 mm		
Depth of filter material cover of lines	2 in.	51 mm		
Depth of filter material beneath lines	3 in.	76 mm		
Grade of perforated lines	3 in/100 ft	2 mm/m		

Source: Adapted from ©2012 *Uniform Plumbing Code*. Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.

20.10 STORM WATER TREATMENT

Until relatively recently, storm water runoff from buildings and paved surfaces was considered harmless and was conducted without treatment, and as rapidly as possible, to receiving streams, rivers, and lakes. However, almost three-quarters of the U.S. population lives on only about 7% of the land. And as our urban watersheds become more and more paved and/or roofed, two problems develop. First, a heavy rain greatly increases peaks in stream flows (because less rain is retained for later, slower release by the action of unpaved surfaces); this accentuated peak–valley pattern of flows makes life more difficult for aquatic flora and fauna. Second, pollutants (especially those accumulated on roadways) are washed into streams—oil, gasoline, antifreeze, fragments of brake linings and tires, and so on, are especially unwelcome deposits. Some design strategies to minimize these impacts, such as roof retention, porous pavement, and on-site groundwater recharging, were discussed in Section 18.6.

With minimal changes in street design, storm water receptacles can be constructed not only to provide access for maintenance, but also to screen out sediment, capture oil and other floating contaminants, and provide a more even outflow (Fig. 20.57). But much more can be done.

Phytoremediation is the science of cleaning polluted soil and water with plants. (The constructed wetlands and algal ponds described in Sections 20.7 and 20.8 apply phytoremediation to sewage treatment.) Phytoremediation extracts, degrades, or contains contaminants. Plants that *extract* take up and accumulate contaminants in their shoots and leaves—when the vegetation is removed from the site, so are the contaminants. Plants that *degrade* break down contaminants (such as hydrocarbons

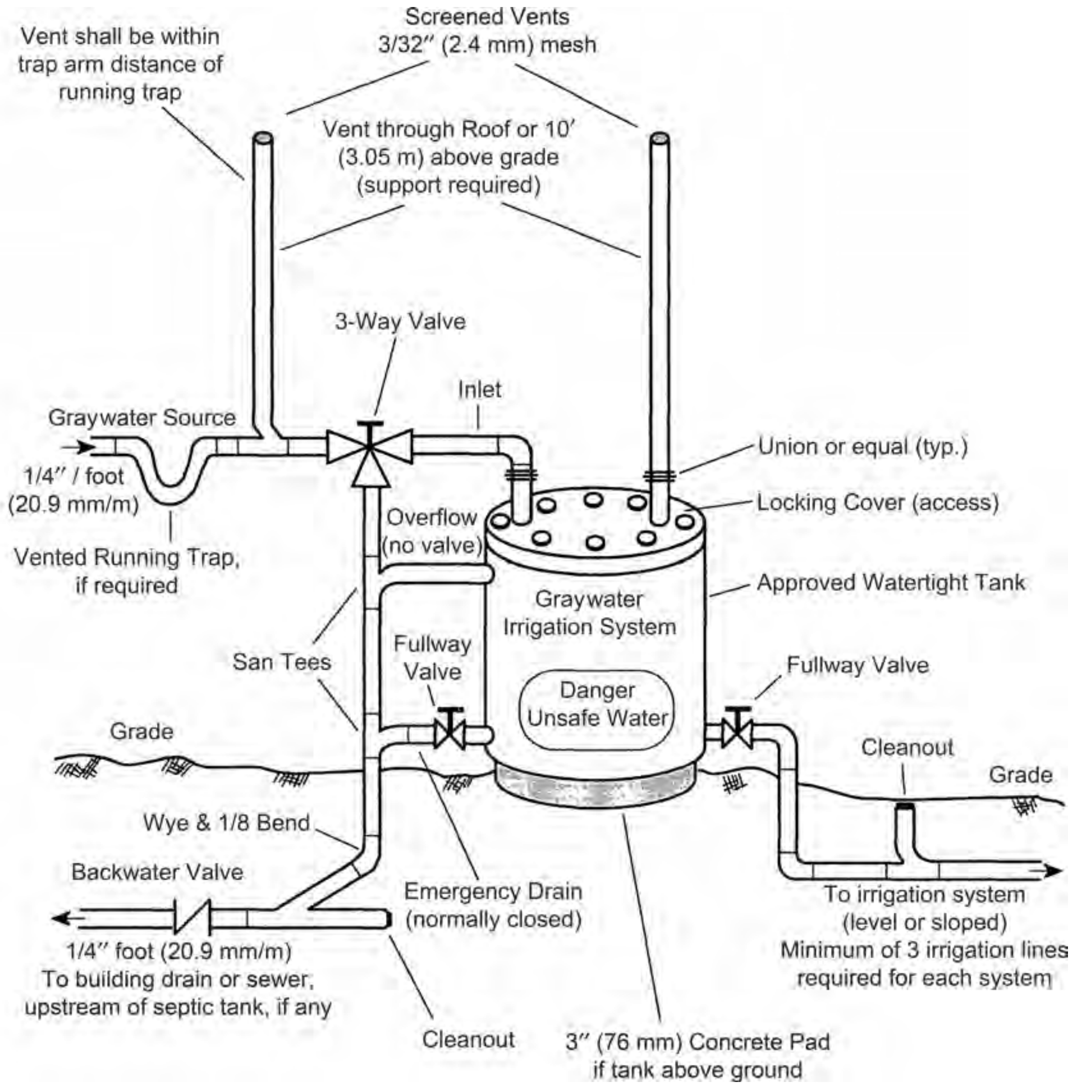


Fig. 20.56 *Schematic diagram of a graywater system with an aboveground, gravity-emptied tank. (©2006* Uniform Plumbing Code. *Reprinted with the permission of the International Association of Plumbing and Mechanical Officials. This copyright material and all points or statements in using this material have not been reviewed by IAPMO. The opinions expressed herein are not representations of fact from IAPMO.)*

and other organic compounds) until they are no longer toxic. Some plants degrade toxins in their root zone, whereas others use elements of organic toxins as food. Plants that *contain* essentially immobilize toxins in long-term storage. However, when the plants die and decompose, long-lived toxins may be released.

For treating storm water, plants are typically incorporated in drainage strips between paved parking areas. The mix of plants is similar to those cited earlier in wetland construction, with sedges and rushes especially effective at cleansing (see Fig. 20.2 for a sample trench). Shade trees could add welcome summer thermal benefits, as well as intercepting and storing some pollutants. The capacity of the planting strip should be sufficient to intercept the "first flush" of rain, which carries the heaviest load of pollutants. Underground drains intercept excess runoff and lead to a capture chamber where floatable contaminants can be periodically removed. The screened, regulated flow from the capture basin will be much gentler on the receiving stream.

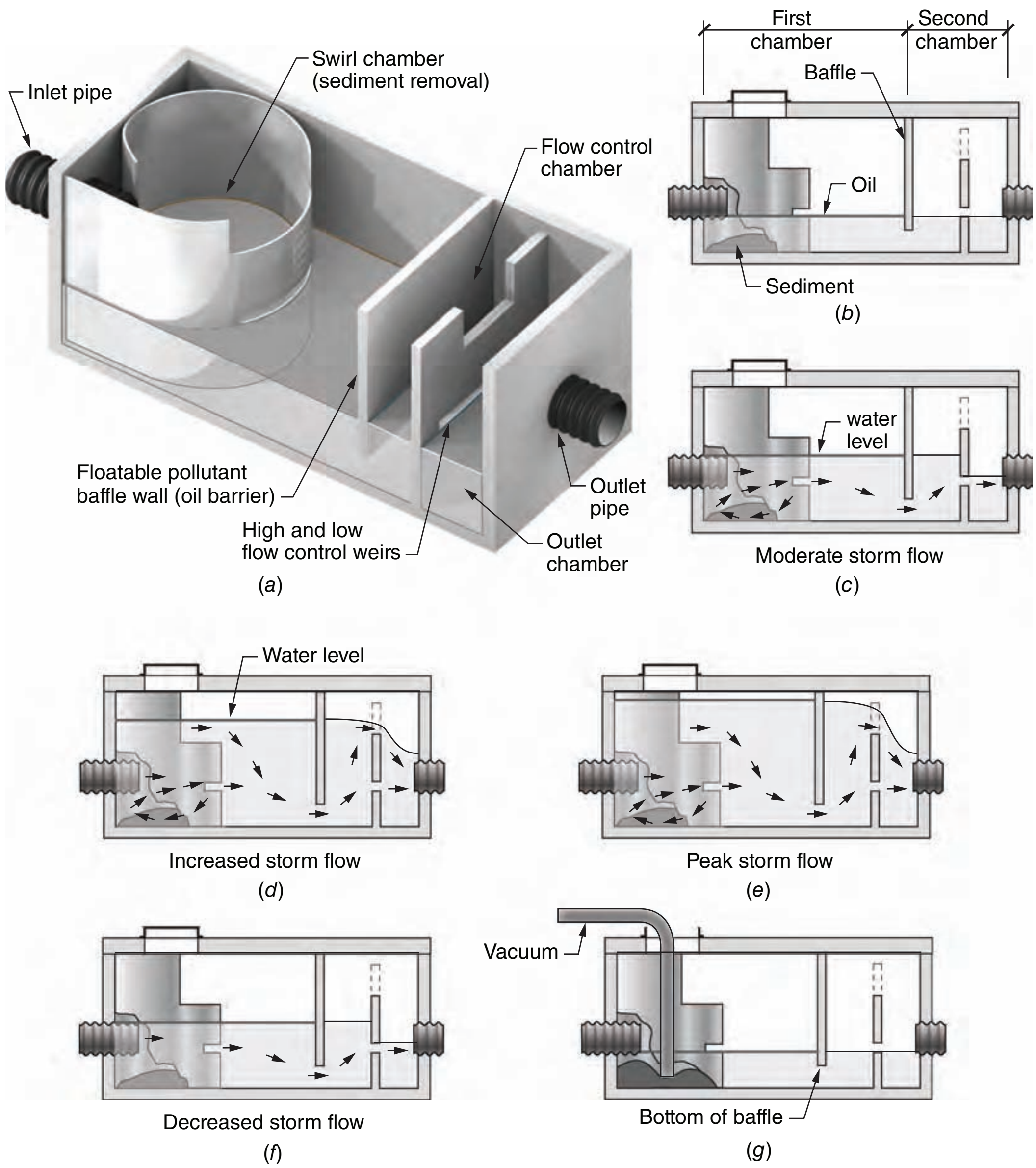


Fig. 20.57 *This Vortechs™ Stormwater Treatment System (a) is designed to separate both floating oily contaminants and sediment from storm water. (b) Rather like a septic tank, two chambers are separated by a baffle. Oil scum and sediment remain in the first chamber. (c) In a moderate storm, water rises above the top of the inlet pipe, greatly reducing velocity and turbulence within the first chamber, encouraging sediment to precipitate to the bottom. (d) As flow increases, rising above the low-flow control (second chamber), oily contaminants accumulated from previous storms float upwards, and more sediment falls out. (e) At the height of storm water flow, usually designed for a 10-year storm, the high-level outlet begins to discharge. Sometimes a peak flow bypass is used. Oily scum and sediment continue to be trapped in the manhole. (f) As the flow subsides, water outflow is controlled, lessening the strain on the storm drainage system. (g) Cleanout, at the lowest water levels, is best done by a vacuum truck. As the grit chamber empties, oily liquids and floating debris drain back toward the inlet and can be removed along with the sediment. Note that the bottom of the baffle between the chambers always remains submerged.*

A new community in Bellevue, Washington, incorporated a storm water treatment facility in a 20-acre (8.1-hectare) public park. Beneath tennis courts, ballparks, picnic areas, and other playing fields, a 300,000-ft^3 (8495-m^3) sediment vault (surface area about 8 acres [3.2 hectares]) slows the flow of storm water, encouraging sediment to drop out. The water then passes to a filter basin of vegetation, sand, and peat for the primary purpose of phosphorus removal. From there it is slowly released to the receiving stream, which then drains into a lake.

Building designers rarely encounter such community-wide pollution control strategies, but parking lots and on-site roadways are encountered on virtually every project. Design for local pollution control, even for seemingly benign storm water, is part of the architect's responsibilities.

20.11 CASE STUDY—WATER CONSERVATION AND RESOURCE DESIGN

Philip Merrill Environmental Center, Chesapeake Bay Foundation

PROJECT BASICS

- Location: Annapolis, Maryland, USA
- Latitude: 38.9°N; longitude: 76.5°W; elevation: near sea level
- Heating degree days: 4707 base 65°F (2615 base 18.3°C); cooling degree days: 3709 base 50°F (2061 base 10°C) for Baltimore, MD; annual precipitation: 42 in. (1063 mm)
- Building type: New construction; commercial offices and interpretive center
- Building area: 32,000 ft^2 (3000 m^2); two occupied stories
- Completed December 2000
- Client: The Chesapeake Bay Foundation
- Design team: SmithGroup (and consultants)

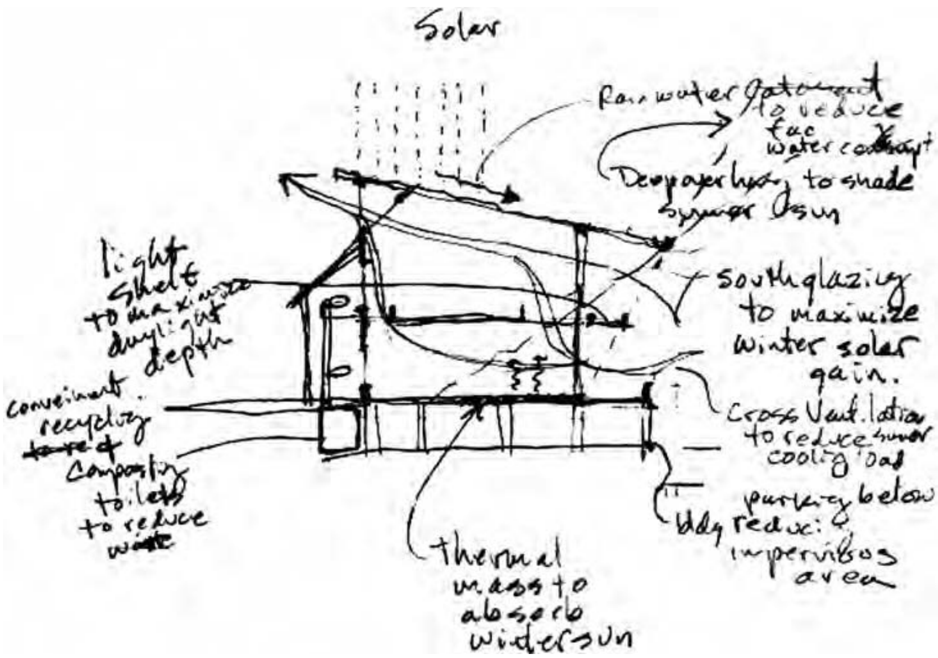


Fig. 20.58 *Conceptual design sketch showing the earliest concept of the Philip Merrill Environmental Center and illustrating how the form of the building was directly related to the environmental goals for the project. This sketch by the design team is an example of how early goal setting allows designers to shape a building to respond to goals, thus creating an integrated design. (© SmithGroup; used with permission.)*

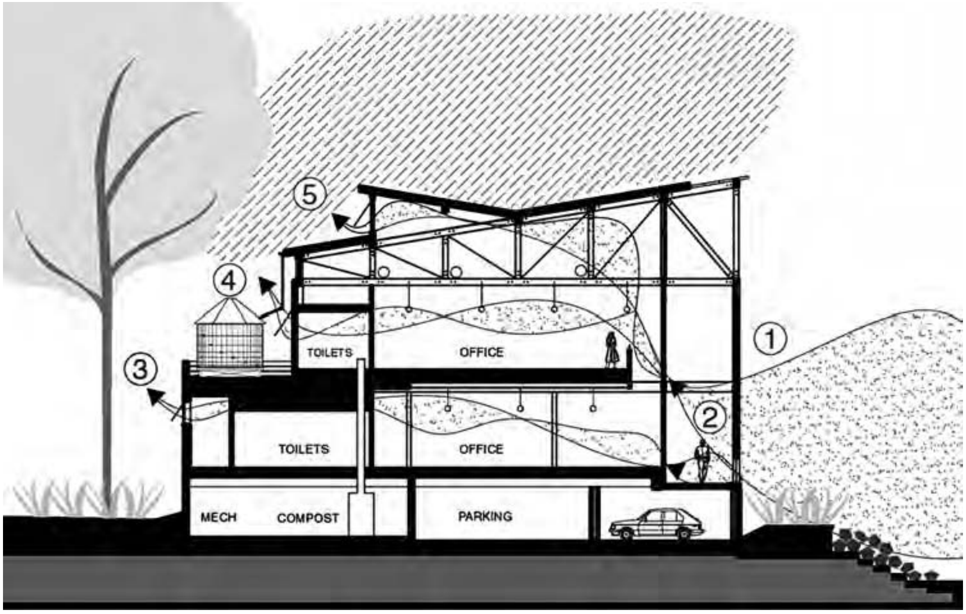


Fig. 20.59 Schematic design diagram illustrating how the conceptual design idea was refined, and the role that natural ventilation, passive solar heating, rainwater collection, and daylighting and views played in shaping the building. Energy and water are clearly focal elements. (© SmithGroup; used with permission.)

Background. The Philip Merrill Environmental Center was the first LEED Platinum building in the United States. Elements of the design process for the Environmental Center are presented in the following sections, in order to emphasize the critical importance of an appropriate design process to the development of high-performance buildings. Design team and client values were important to the success of this project—and led to the development of explicit and aggressive green design intent and criteria. Concern for energy efficiency and water conservation led to much of the distinctive form of the building—especially the signature water storage tanks on the entry façade. (The information that follows was provided by SmithGroup.)

Context. The Chesapeake Bay Foundation (CBF) is an environmental advocacy, restoration, and education organization headquartered in Annapolis, Maryland. Before the creation of the Philip Merrill Environmental Center, CBF's facilities included three properties in Annapolis and a small building outside of town. The functioning and unity of the organization suffered from the disparate locations and consequent separation of departments, justifying the creation of a new headquarters that could unify and house CBF in an optimum environment.

Design Intent. The new headquarters would not only house the Foundation, but would also be a reflection on CBF's mission. It would serve as a paragon for the Bay's watershed region of sustainable development—"walking the talk," "practicing what CBF preaches." The design was to emulate the regional vernacular and utilitarian functions of working on the Bay. The building was to respond to habitats, vegetation, soils, buffer zones, views, solar orientation, topography, prevailing wind direction, and functional requirements. The organization of the elements on the site would tell the story of CBF's mission to educate and involve the public in taking responsibility for the health of the Bay.

The leading principles behind the design were as follows:

- Set a precedent for sustainable development on the Chesapeake Bay.
- Provide for the functional needs of CBF.
- Create an effective work environment.
- Embody a sense of unity and connectivity.

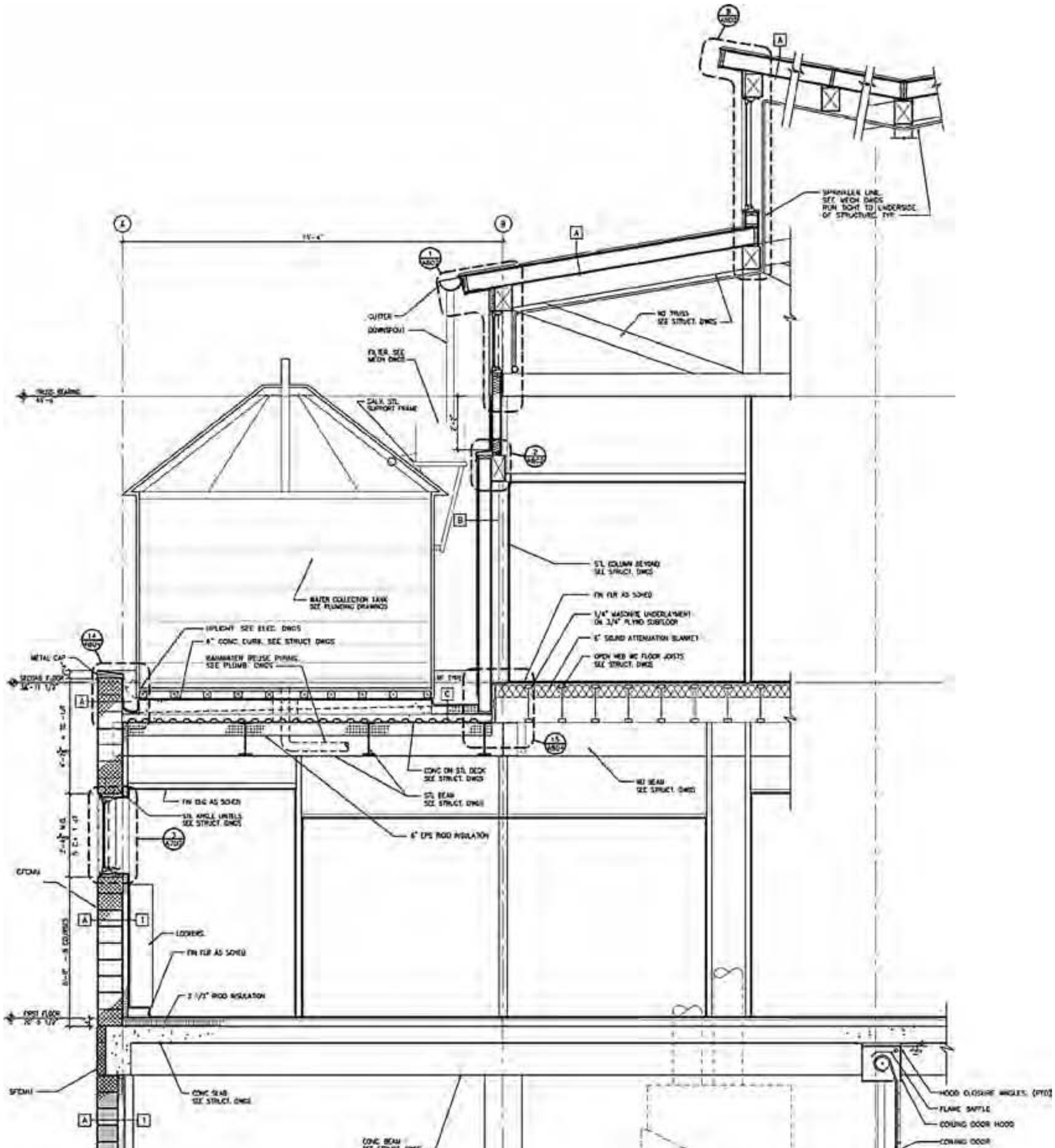


Fig. 20.60 *Section through the Philip Merrill Environmental Center developed during the construction documents phase. The water storage tanks, which are a signature element of the final design, have evolved from concept to buildable artifact. (© SmithGroup; used with permission.)*

Fig. 20.61 *North (inland) façade of the Philip Merrill Environmental Center showing the visual impact of rainwater collection intent and solution. Water conservation has informed this façade. (Photo © 2004 Walter Grondzik; all rights reserved.)*

Fig. 20.62 *South (bay side) façade of the Philip Merrill Environmental Center showing PV panels, daylighting/solar apertures, and shading elements. Energy collection has informed this façade. (Photo © 2004 Walter Grondzik; all rights reserved.)*

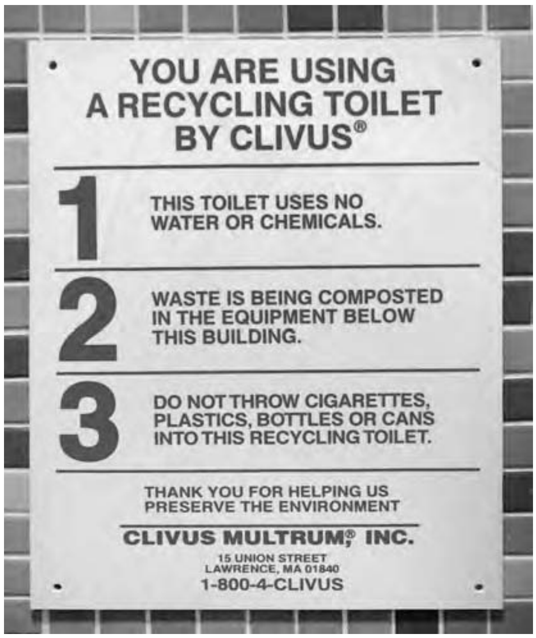


Fig. 20.63 *Clivus Multrum sign above composting toilets to help educate users. (©Alison Kwok; all rights reserved.)*

Fig. 20.64 *Sign in the toilet stall to remind users about caring for the health of the bay. (© Alison Kwok; all rights reserved.)*

- Push the envelope of green building.
- Reflect the utilitarian nature of CBF.
- Mesh indoor and outdoor spaces.
- Integrate CBF's departments while preserving distinction.
- Enhance public service.
- Facilitate an educational experience.

Design Criteria and Validation. The project was intended to achieve a LEED Platinum rating. At the time design commenced, LEED was a largely unknown rating system in its pilot phase of development. The LEED system was used both as a benchmark and as an assessment tool—a way of validating the design's sustainability. Energy modeling using ENERGY 10 was performed during the preliminary design phases. The overall energy modeling during subsequent phases used Trace.

Post-Occupancy Validation Methods. A full year of monitoring and POE was performed by the National Renewable Energy Laboratory (NREL), from November 2001 through November 2002. The NREL provided the monitoring equipment to measure the resource consumption (water, electricity, propane) of the building and to measure the energy generated by the building. The NREL then compared these data with the performance of a computer-simulated baseline energy model, developed to address the minimum standards of ASHRAE Standard 90.1, based upon ASHRAE/IESNA 90.1-2001. In November 2004 a post-occupancy, web-based survey was conducted for the Philip Merrill Environmental Center via

Fig. 20.65 *Clivus Multrum composting toilet, with a bucket of sawdust nearby for users to sprinkle with toilet waste. (© Alison Kwok; all rights reserved.)*

the University of California, Berkeley. The survey, reporting a 78% response rate, showed overall success in daylighting, air quality, electric lighting, and access to views, but poorer scores regarding satisfaction with temperatures, noise levels, and speech privacy. Of the 150 buildings surveyed by the University of California, Berkeley, the Philip Merrill Environmental Center received the second-highest overall satisfaction score.

Performance Data. Information available to date suggests substantial design team success in key areas of sustainable building—particularly material, water, and energy conservation:

- The building achieved LEED Platinum rating.
- Rainwater, collected via the roof into cisterns, supplies 73% of the Environmental Center's water; the remaining percentage is supplied by a well that is on site. The Water Environment Research Foundation reports, "Water consumption is 94% less than a conventional building, and the center's total four-year average water savings were approximately 7600 m^3 (2 million gallons), saving CBF nearly

$8000 in water and sewer costs. Average daily water use is 0.34 m^3/d (90 gpd), more than two-thirds of which is harvested rainwater (normal daily use would be about 5.7 m^3/d [1500 gpd] without water-saving technologies). Composting toilets save approximately $2100 per year on water and sewage rates compared to an office of 100 people with conventional toilets" (WREF, 2010).

- While the end goal is to reuse and treat all liquids and waste on site, currently, due to the use of composting toilets and water-conserving systems, the outflow to the sewer network is 10% of what a typical design would be producing. Compost that is produced, after the several-months-long process of decomposition, is utilized for on-site landscape purposes.
- From November 2001 to November 2002, average net site energy use was 39.9 $kBtu/ft^2/yr$ (453.2 $MJ/m^2/yr$); the computer-simulated baseline model was performing at 53.3 $kBtu/ft^2/yr$ (604.8 $MJ/m^2/yr$).
- From November 2001 to November 2002, average net source energy use was 124.3 $kBtu/ft^2/yr$ (1412 $MJ/m^2/yr$); the computer-simulated baseline model was performing at 159.6 $kBtu/ft^2/yr$ (1812 $MJ/m^2/yr$).
- All wood was obtained from renewable resources; more than 50% of building materials were obtained from within a 300-mile (480-km) radius of the site.
- The project received a Grand Award, Building Team Project of the Year, from *Building Design & Construction* magazine in 2001. The building was named one of the AIA/COTE Top Ten Green Projects in 2001; it tied for first place in the "places of work" category of the NESEA Green Building Awards in 2003; it also achieved a first place in the ASHRAE Technology Awards of 2001 under the "Commercial New" division.

FOR FURTHER INFORMATION

Heerwagen, Judith and Leah Zagreus. 2005. "The Human Factors of Sustainable Building Design: Post Occupancy Evaluation of the Philip Merrill Environmental Center, Annapolis, MD." *Summary Report for US Department of Energy*, April 2005.

Griffith, M. et al. "Analysis of the Energy Performance of the Chesapeake Bay Foundation's Philip Merrill Environmental Center." *Technical Report for the National Renewable Energy Laboratory*. April 2005.

National Renewable Energy Laboratory: http://www.nrel.gov/

U.S. Department of Energy. Energy Efficiency and Renewable Energy, Building Technologies Program, Buildings Database: http://eere.buildinggreen.com

U.S. Department of Energy. High Performance Buildings Database: https://buildingdata.energy.gov/hpbd/

Water Environment Research Foundation. 2010. "When to Consider Distributed Systems in an Urban and Suburban Context": www.werf.org/c/Decentralizedproject/Philiip_Merrill_Cent.aspx

References and Resources

Composting Toilet World. www.compostingtoilet.org/

Converse, J., et al. 1978. *Design and Construction Manual for Mounds*. Small Scale Waste Management Project, University of Wisconsin Extension. Madison, WI.

EPA. 1993. *Subsurface Flow Constructed Wetlands for Wastewater Treatment*. EPA 832-R-93-008. U.S. Environmental Protection Agency, Office of Water. Washington, DC.

Green, F. B., L. Bernstone, T. J. Lundquist, J. Muir, R. B. Tresan, and W. J. Oswald. 1995a. "Methane Fermentation, Submerged Gas Collection, and the Fate of Carbon in Advanced Integrated Wastewater Pond Systems." *Water Science and Technology*, Vol. 31, No. 12.

Green, F. B., T. J. Lundquist, and W. J. Oswald. 1995b. "Energetics of Advanced Integrated Wastewater Pond Systems." *Water Science and Technology*, Vol. 31, No. 12.

Green, F. B., L. Bernstone, T. J. Lundquist, and W. J. Oswald. 1996. "Advanced Integrated Wastewater Pond Systems for Nitrogen Removal." *Water Science and Technology*, Vol. 33, No. 7.

IAPMO. 2006. *Uniform Plumbing Code*. International Association of Plumbing and Mechanical Officials. Walnut, CA.

IAPMO. 2012. *Uniform Plumbing Code*. International Association of Plumbing and Mechanical Officials. Walnut, CA.

ICC. 2012. *International Plumbing Code*. International Code Council. Washington, DC.

Ludwig, A. 1997. *Create an Oasis with Greywater*. Poor Richard's Press. Santa Maria, CA.

Milne, M. 1976. *Residential Water Conservation*. U.S. Office of Water Research and Technology, Department of Commerce, NTIS. Springfield, VA.

National Small Flows Clearinghouse. 1997. "Lagoon Systems Can Provide Low-Cost Wastewater Treatment." *Pipeline,* Vol. 8, No. 2. National Small Flows Clearinghouse. Morgantown, WV.

Nelson, G. 1981. "Graywater Heat Recovery." *Solar Age*, August 1981.

Oswald, W. J., C. G. Golueke, R. C. Cooper, H. K. Gee, and J. C. Bronson. 1963. "Water Reclamation, Algal Production and Methane Fermentation in Waste Ponds." *International Journal of Air and Water Pollution*, Vol. 7.

Oswald, W. J., A. Meron, and M. D. Zabat. 1970. "Designing Waste Ponds to Meet Water Quality Criteria." *Proceedings of the Second International Symposium on Waste Treatment Lagoons*, Kansas City, MO.

Oswald, W. J. 1990. "Advanced Integrated Wastewater Pond Systems." *Supplying Water and Saving the Environment for Six Billion People: Proceedings of the 1990 American Society of Civil Engineers Convention,* Environmental Engineering Division, November 5–8, San Francisco.

Oswald, W. J., F. B. Green, and T. J. Lundquist. 1994. "Performance of Methane Fermentation Pits in Advanced Integrated Wastewater Pond Systems." *Water Science and Technology*, Vol. 30, No. 12.

CHAPTER 21

Solid Waste

FOR SOME DESIGNERS, the last building distribution system considered is the one involving the bulkiest items: the flow of supplies in and solid waste out. Because this system usually is not seen as consuming building energy or requiring specialized equipment, it ordinarily becomes a low-priority system in the design process. Yet provisions for delivery of supplies, and especially for the collection and storage of solid wastes, can be more space-consuming than water/waste systems, can present a fire danger, and can create serious local environmental problems. The separation of solid waste for resource recovery involves significant energy and environmental consequences. Finally, mechanical equipment associated with solid waste is now commonly part of waste management systems.

21.1 WASTE AND RESOURCES

Since the late 1940s, there has been a marked increase in the amount of packaging material used for consumer products. Where shoppers once refilled reusable containers for bulk supplies at the market, for example, they now buy food in bags or cans that are discarded after use. This trend has increased space demands in the store, where shelves of cans are required instead of a bin of bulk products—and the same is true for the home, where such packaging soon turns into waste and must be stored until garbage collection day. Energy is required to make the boxes, bags, cans, and other containers; transport them; and collect them as trash. Devices such as trash compactors add both space and energy requirements to the use/disposal process. Landfills for garbage disposal are filling rapidly as solid waste flows increase. Methane and leachate from these landfills are potential environmental problems.

There may not be much that building designers can do about these increased packaging trends. But the solid wastes from buildings contain important resources (Tables 21.1 and 21.2), and a designer can help society to recover those resources rather than burying them in landfills or dumping them in the ocean. Furthermore, buildings themselves can be designed for construction materials recovery upon remodeling or demolition.

The resources within solid waste can be divided into the high-grade resources represented by recyclable materials and the low-grade resources of heat and by-products obtainable from the burning or decomposing of combustible solid wastes.

(a) High-Grade Resources

These include metals such as aluminum and steel, paper and paperboard, wood, and some plastics. For building designers, these pose the problem of storage while awaiting collection. For many of these materials, reuse in their present form is desirable, which eliminates compaction as a storage strategy. Table 21.1 compares uncompacted and compacted volumes of various recyclable materials.

TABLE 21.1 Typical Recyclable Materials from Building Operations

Category	Product	Recycling Label	Material Description	Conversion, Volume to Weight	
				I-P Units	SI Units
Paper	Ledger paper, white letterhead	SWL	Sorted white ledger, high-grade white paper	Uncompacted: 1 yd^3 = 500 lb Compacted: 1 yd^3 = 750 lb	Uncompacted: 1 m^3 = 297 kg Compacted: 1 m^3 = 445 kg
	Computer paper	CPO	Computer printout	Uncompacted: 1 yd^3 = 500–600 lb Compacted: 1 yd^3 = 1000–1200 lb	Uncompacted: 1 m^3 = 297–356 kg Compacted: 1 m^3 = 593–712 kg
	Colored paper	SCL	Sorted color ledger	Uncompacted: 1 yd^3 = 500 lb Compacted: 1 yd^3 = 750 lb	Uncompacted: 1 m^3 = 297 kg Compacted: 1 m^3 = 445 kg
	Newspaper	Mix	Newsprint	Uncompacted: 1 yd^3 = 350–500 lb Compacted: 1 yd^3 = 750–1000 lb	Uncompacted: 1 m^3 = 208–297 kg Compacted: 1 m^3 = 445–593 kg
	Magazines	Mix	Clay-coated paper	Not available	Not available
	Telephone books	Mix	Mixed papers-adhesives	1 book = 1–3 lb	1 book = 0.5–1.4 kg
	Cereal boxes	Mix	Coated paperboard	Not available	Not available
	Shipping boxes	OCC	Old corrugated cardboard	Uncompacted: 1 yd^3 = 285 lb Compacted: 1 yd^3 = 500 lb	Uncompacted: 1 m^3 = 169 kg Compacted: 1 m^3 = 297 kg
Glass	Food jars, beverage bottles	1 2 3	Amber glass Green glass Clear glass	Loose, whole: 1 yd^3 = 600 lb Manually crushed: 1 yd^3 = 1000 lb Mechanically crushed: 1 yd^3 = 1800 lb	Loose, whole: 1 m^3 = 356 kg Manually crushed: 1 m^3 = 593 kg Mechanically crushed: 1 m^3 = 1068 kg
Plastic	Beverage containers	PET	Polyethylene terephthalate	Whole: 1 yd^3 = 30 lb	Whole: 1 m^3 = 18 kg
	Milk containers	HDPE	High-density polyethylene	Whole: 1 yd^3 = 25 lb Crushed: 1 yd^3 = 50 lb Compacted: 1 yd^3 = 600 lb	Whole: 1 m^3 = 15 kg Crushed: 1 m^3 = 30 kg Compacted: 1 m^3 = 356 kg
	"Clamshell" containers	—	Polystyrene plastic foam	Not available	Not available
	Film plastic	LDPE	Low-density polyethylene	Not available	Not available
Metals	Beverage cans		Aluminum/ bimetal	Whole: 1 yd^3 = 50–70 lb Crushed: 1 yd^3 = 300–450 lb	Whole: 1 m^3 = 30–42 kg Crushed: 1 m^3 = 178–267 kg
	Food and beverage cans		Steel with tin finish	Whole: 1 yd^3 = 125–150 lb Crushed: 1 yd^3 = 500–850 lb	Whole: 1 m^3 = 74–89 kg Crushed: 1 m^3 = 297–504 kg
Miscellaneous	Pallets		Wood	Not available	Not available
	Food waste and liquids		Organic solids	55-gal drum = 415 lb	208 L drum = 188 kg
	Yard waste		Organic solids	Leaves, uncompacted: 1 yd^3 = 250 lb Leaves, compacted: 1 yd^3 = 450 lb Wood chips: 1 yd^3 = 500 lb Grass clippings: 1 yd^3 = 400 lb	Leaves, uncompacted: 1 m^3 = 148 kg Leaves, compacted: 1 m^3 = 267 kg Wood chips: 1 m^3 = 297 kg Grass clippings: 1 m^3 = 237 kg
	Used motor oil		Petroleum product	1 gallon = 71 lb	1 L = 8.5 kg
	Tires		Rubber	1 passenger car = 20 lb 1 truck = 90 lb	1 passenger car = 9 kg 1 truck = 41 kg

Source: Reprinted by permission from AIA: Ramsey/Sleeper, *Architectural Graphic Standards*, 10th ed., © 2000 by John Wiley & Sons.

TABLE 21.2 Solid Waste Sources in Building Operation

		Types of Waste Generated	*Quantities of Waste Generated*	
Classification	**Occupancy**	**(percent, where available)**	**I-P Units**	**SI Units**
Residential	Studio or 1-bedroom apartment	Newspaper (38/43)[a] Plastic (18/7)[a] Miscellaneous (13/18)[a]	1–1.5 yd^3/unit/month (200–250 lb) or 2.5 lb/person/day	0.8–1.1 m^3/unit/month (91–113 kg) or 1.1 kg/person/day
	2- or 3-bedroom apt. or single-family house	Metals (14/9)[a] Compost (10/15)[a] Glass (2/8)[a]	1.5–2 yd^3/unit/month (250–400 lb) or 2.5 lb/person/day	1.1–1.5 m^3/unit/month (113–181 kg) or 1.1 kg/person/day
Commercial	Office	Plastics, compost, used oil, metals, and glass (30)[b] High-grade paper (29)[b] Mixed papers (23)[b] Newspaper (10)[b] Corrugated cardboard (8)[b]	1.5 lb/employee/day or 1 yd^3/10,000 ft^2/day (includes 0.5 lb of high-grade paper/employee/day)	0.7 kg/employee/day, or 0.8 m^3/1,000 m^2/day (includes 0.2 kg of high-grade paper/employee/day)
	Department store Wholesale/retail Shopping center	Corrugated cardboard, compost, wood pallets, high-grade paper, and plastic film	1 yd^3/2,500 ft^2/day 70 lb/$1000 sales/day 2.5 lb/100 ft^2/day	0.8 m^3/250 m^2/day 32 kg/$1000 sales/day 1.1 kg/100 ft^2/day
	Supermarkets	Corrugated cardboard, compost, and wood pallets	1 yd^3/2,500 ft^2/day	0.8 m^3/250 m^2/day
	Restaurants/entertainment	Compost (38)[b] Corrugated cardboard (11)[b] Newsprint (5)[b] High-grade paper (4)[b]	Cafeteria, 1 lb/meal Fast food, 200 lb/$1000 sales Restaurant, 1.5 lb/meal	Cafeteria, 0.45 kg/meal Fast food, 91 kg/$1000 sales Restaurant, 0.7 kg/meal
	Drug stores	Corrugated cardboard and high-grade paper	1 yd^3/2,000 ft^2/day	0.8 m^3/200 m^2/day
	Banks, insurance companies	High-grade paper, mixed paper, and corrugated cardboard	0.75 lb high-grade paper/person/day (survey required)	0.34 kg high-grade paper/person/day (survey required)
Hotels and motels (not including restaurants)	High occupancy	Glass, aluminum, plastic, high-grade paper, newspaper, and corrugated cardboard	0.5 yd^3/room/week 3.2 lb/room/day	0.38 m^3/room/week 1.45 kg/room/day
	Average occupancy		0.17 yd^3/room/week 1.7 lb/room/day	0.13 m^3/room/week 0.8 kg/room/day
Institutional	Hospitals	Compost, high-grade paper, biomedical waste, corrugated cardboard, glass, and plastics	1 yd^3/5 occupied beds/day	0.8 m^3/5 occupied beds/day
	Nursing homes Retirement homes		1 yd^3/15 persons/day 1 yd^3/20 persons/day	0.8 m^3/15 persons/day 0.8 m^3/20 persons/day
Educational	Grade school High school Universities	High-grade paper, mixed paper, newspaper, corrugated cardboard, compost, plastic, glass, and metals	1 yd^3/8 rooms/day 1 yd^3/10 rooms/day (Survey required)	0.8 m^3/8 rooms/day 0.8 m^3/10 rooms/day (Survey required)

Source: Reprinted by permission from AIA: Ramsey/Sleeper, *Architectural Graphic Standards*, 10th ed., © 2000 by John Wiley & Sons.

[a]Percent by volume/percent by weight.

[b]Percent by volume.

Glass is especially suitable for recycling when it can be reused after simple washing, as in the case of beer and soft-drink bottles. Returnable (for deposit) bottles and cans have measurably decreased roadside litter in states that require such policies. Newspaper is so readily stored and recycled that in many communities, charitable groups or service organizations recover newspapers for profit. Recycled paperboard can easily save 50% of the energy that would be required to produce pulp from virgin material.

The recovery of aluminum saves 96% of the energy necessary to process it originally. Because the aluminum production process is dependent upon electricity, the recycling of aluminum is doubly attractive. Energy conservation in aluminum production had developed to the point that only 82% as much energy was needed to make a pound of aluminum in 1982 as in 1972. More than a third of that reduction was attributable to aluminum-recycling programs; the remainder came from improvements in the production process. As for steel, recycling can produce a 52% energy savings compared to the use of virgin material.

Wood has become more valuable as fiber than as fuel. Wood chips and scraps that once were burned or buried are now recycled to become oriented strand board (OSB) used in structural insulated panels (SIPs), window frames, and many other aspects of building and furniture construction.

Plastics are more difficult to recycle. Regulations and consumer preferences discourage the use of recycled plastics in food-related items. The plastics from items such as soft-drink containers, margarine tubs and lids, and milk jugs, however, can be reprocessed into plastic pellets, which are cheaper than virgin plastic pellets. These pellets are then made into nonfood items—toys, building products, sports products, and other things.

(b) Low-Grade Resources

These resources include materials for which recycling is impractical but that are combustible. Low-grade resources include gaseous wastes, liquid and semiliquid wastes, and solid wastes. Industrial and commercial processes can generate wastes of all types, including some with very high heat content and some that are very toxic. Although recovering heat by burning such materials seems better than landfilling them, air pollution regulations have severely restricted simple trash burning as a means of solid waste disposal. Incinerators must meet increasingly strict regulations and, as a result, are very rarely installed in buildings. A better option is often to compost such materials in landfills. The methane generated in landfills can then be used as a high-grade fuel.

Where large quantities of mixed trash, garbage, and other refuse are collected, special resource-recovery plants can be built to recover materials, produce useful steam for electricity generation, and reduce the flow of waste to landfills. In this energy-intensive process, mixed garbage is shredded and blown through large "air classifiers" that separate the organic (burnable) wastes from metals and glass. The burnable wastes are then used as fuel, under controlled combustion, to generate electricity. The metals are further separated magnetically into ferrous and nonferrous classes; these and the glass are then recycled.

The Energy Efficient Resource Recovery (E2R2) integrated infrastructure facility that was proposed for California Polytechnic State University, San Luis Obispo, combining wastewater treatment and solid waste processing, was introduced in Fig. 20.42. The solid waste facility is shown in Fig. 21.1.

The schematic design for solid waste processing (SWP) in the proposed E2R2 facility involves transporting unsorted solid waste to a central processing facility located on campus. Materials will then be sorted using mechanical equipment and processing. The composition of the solid waste stream is expected to be 70% organic materials, suitable for composting, and 815 tons (739 Mg) per year of recyclable materials (i.e., metals, glass, paper, and cardboard). Roughly 10% of the solid wastes are anticipated to be unsuitable for either recycling or composting. These "inert" materials will be disposed of at the local landfill.

Once the nonrecyclable, organic materials are separated, the design calls for them to be uniformly ground and combined with sludge (from the city of San Luis Obispo's wastewater treatment plant) or manure (from the university's farming operations) to achieve a proper carbon-to-nitrogen balance. Given the dynamic nature of the recyclable materials market, it is anticipated that, at times, some potentially recyclable paper will be included in the compost operations.

After mixing, the organic materials will be loaded into a high solids anaerobic digester to undergo methane fermentation. The biogas generated by the fermentation process will be harvested and stored on site. Prior to use, the biogas will be scrubbed (processed) to remove impurities, making it suitable for use as fuel. A portion of the methane will be used to heat the digester, and the excess will power a micro fuel cell to generate electricity for campus use. Other potential uses include using methane in the campus boiler, as an alternative to gasoline in the university's automobile and truck fleet, and even to power an ultra-high-temperature hazardous waste disposal system.

The anaerobic digestion process is projected to generate 180,000 ft^3 (5098 m^3) per day of biogas. The energy content of the methane in this biogas is estimated at 35×10^9 Btu (36.9×10^9 kJ) per year.

After being unloaded from the high solids digester, the remaining biosolids will be pressed to recover bacteria-rich liquids, which are useful

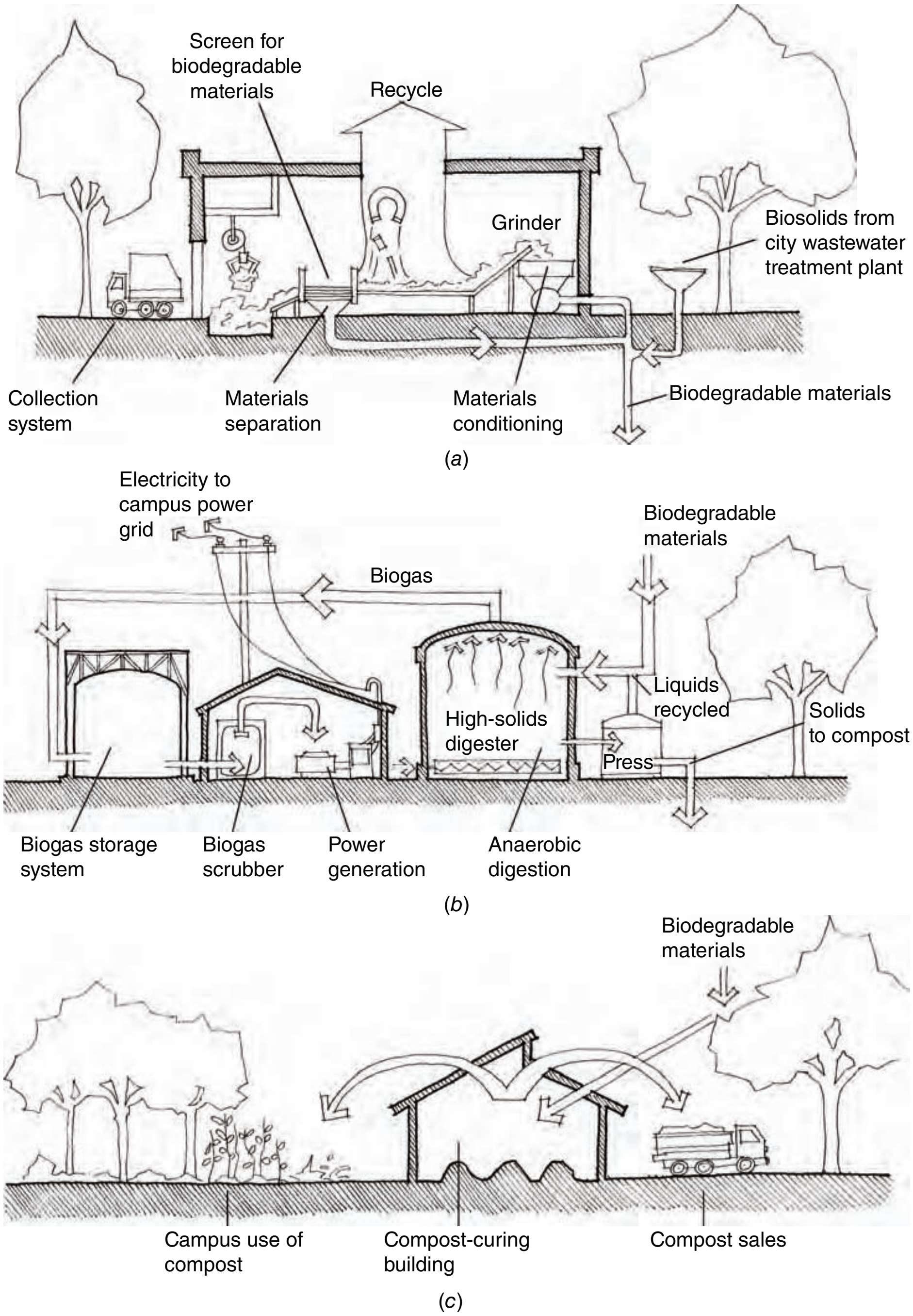


Fig. 21.1 *Schematic design proposal for solid waste processing at the proposed E2R2 facility at California Polytechnic State University, San Luis Obispo, California. Unsorted solid wastes are separated into recyclable, organic, and inert materials (a). The organic materials are ground, combined with sludge from the city's sewage treatment plant, and loaded into the high-solids digester (b) to undergo anaerobic fermentation. The biogas generated by the fermentation process is scrubbed to remove impurities from the methane, making it suitable for use as a fuel to heat the digester and to power a micro fuel cell to generate electricity for the campus. Biosolids from the digester are pressed, and the liquid, rich in anaerobic bacteria, is then used to inoculate the next anaerobic fermentation cycle. Pressed biosolids are mixed with nutrient-rich algae from the adjacent wastewater facility and pasteurized in compost-curing buildings (c). Once cured, the compost can be used on landscaped areas or farm lands or sold to local gardeners. (Courtesy of Professor Douglas Williams, Agricultural Engineering Department, and Professor Daniel Panetta, Architecture Department, Cal Poly, San Luis Obispo. Redrawn by Dain Carlson.)*

in inoculating the next batch of materials for the digester. The dewatered biosolids will then be mixed with algae from the adjacent AIWPS (Advanced Integrated Wastewater Pond System) facility to create a nutrient-rich compost. This compost will be available for use on the campus's landscape and its farm lands or for sale to local gardeners. Yearly compost production is anticipated to exceed 5000 tons (4535 Mg) air-dried weight.

As an added touch, straw bale construction is proposed for the E2R2 facility buildings. Currently, plans call for an education and laboratory building, a shared control office for wastewater treatment and solid waste processing operations, a solid waste processing building, and on-site student housing. Straw bale construction is advantageous because of its affordability, as well as its exceptional insulation and noise mitigation characteristics. In addition, using rice straw for construction will help provide an alternative to burning waste straw from California's rice crop.

Conventional landfills accept unsorted garbage from a huge variety of sources. Over many years, anaerobic combustion in such enclosed landfills generates methane gas, a usable resource, as described previously.

21.2 RESOURCE RECOVERY: CENTRAL OR LOCAL?

In general, the more thoroughly mixed the different types of solid waste, the harder it is to recover their high- and low-grade resources. From an energy conservation viewpoint, solid wastes should be kept as separate as possible; glass bottles should be washed and reused rather than broken and recycled, and unrecyclable but burnable solid wastes should be kept clean and dry until they can be burned or composted. The earlier that different types of metals are separated, for example, the less energy spent later to separate aluminum from steel, and so forth. Organic food wastes could be composted for use on site rather than ground up and added to the load on the sewage treatment system.

There are two disadvantages, however, to local solid waste separation (at the point of their discard)—one cultural, one physical. Keeping solid wastes separate requires somewhat more effort and time on the part of the consumer. Rather than dumping everything in a garbage can, the resource-conscious consumer will take the time to understand the local recycling procedures and separate garbage and recyclables in accordance with such requirements. Composting in urban apartments presents a unique space-odor challenge.

This disadvantage of slightly more work and time for waste separation is compounded by the physical disadvantage of the floor or cabinet space taken up by multiple containers. In communities fortunate enough to have recycling-oriented garbage service (such a service, it should be noted, is expanding throughout the U.S.), these containers can be carried out and lined up to await garbage collection. The trucks used for this purpose are complex assemblages of various bins rather than one massive cavern with a compactor. In many communities, however, each pile of recyclable material at home must be dealt with separately, either collected by a specialized handler (nonprofit agencies, for example) or taken to a different collection point—a disadvantage in terms of both the time and energy used in transportation. Clearly, the designer's incentive to include recycling in building function will be stronger where recycling collection is well established.

The characteristics of local waste separation, then, are increased consumer time and building space requirements; see Tables 21.2 and 21.3. Central waste separation is characterized by energy-intensive (and noisy) industrial processes. Sections 21.3 and 21.4 offer a detailed look at the consequences of local waste separation for some common building types.

The massive quantities of solid waste generated in urban areas give rise to the terms *urban mines* and *urban forests*. To the extent that these solid wastes can be turned into resources, savings can be realized in various areas—transportation costs and energy consumption, land area set aside for landfills, and the replacement of virgin materials by these recycled resources.

21.3 SOLID WASTE IN SMALL BUILDINGS

Today, most occupants of small buildings have to choose between the separation of waste or the mixing of garbage. Where food preparation is involved, as in residences or restaurants, the

TABLE 21.3 Space Planning for Solid Waste

PART A. I-P UNITS			
		Exterior Area Required	
Occupancy	Building Area ft^2	For Trash ft^2	For Recyclable Materials, ft^2
Nonresidential	0–5000	12	12
	5001–10,000	24	24
	10001–25,000	48	48
	25000+	Each additional 25000 ft^2 require 48 ft^2 each, trash and recyclables	
Multifamily Residential	2–6 Units	12	12
	7–15 Units	24	24
	16–25 Units	48	48
	25+ Units	Each additional 25 dwelling units require 48 ft^2 each, trash and recyclables	
PART B. SI UNITS			
		Exterior Area Required	
Occupancy	Building Area m^2	For Trash m^2	For Recyclable Materials, m^2
Nonresidential	0–465	1.1	1.1
	466–929	2.2	
	930–2323	4.5	
	2323+	Each additional 2323 m^2 require 4.5 m^2 each, trash and recyclables	
Multifamily Residential	2–6 Units	1.1	1.1
	7–15 Units	2.2	2.2
	16–25 Units	4.5	4.5
	25+ Units	Each additional 25 dwelling units require 4.5 m^2 each, trash and recyclables	

Source: Reprinted by permission from AIA: Ramsey/Sleeper, *Architectural Graphic Standards*, 10th ed., © 2000 by John Wiley & Sons.

variety of special containers can reach surprising complexity (Fig. 21.2).

As the point of origin for so many types of solid waste, the kitchen is often the location of waste separation and storage. There is an inherent conflict, however, between the kitchen's frequently hot, humid environment and the need for a cool, dry, well-aired place for solid wastes. This suggests that a space—pantry, air-lock entry, cabinet, or closet—should be provided that opens to the kitchen on one side, and to the outside on the other (Fig. 21.3). Through such an arrangement, both the daily depositing of solid waste and weekly waste removal are made easy, and the near-outdoor conditions are better for the waste in many climates. It is also important that the waste storage area be designed in a manner that makes it easy to clean.

(a) Garbage Disposer

This common appliance (Fig. 21.4) is usually installed below the kitchen sink, often in conjunction with a dishwasher. It grinds up organic food scraps and sends them on to the sewer. This device is a boon to central garbage collection because it lightens the weight of the garbage can and adds less moisture to the garbage (which thus can be burned more efficiently). Finely chopped organic matter has a better chance to biodegrade at the wastewater treatment plant than in a tightly packed landfill. However, garbage disposer units require both water and energy. Water must be kept running during the grinding process in order to keep the blades free of debris, and cool the grinder's motor. In all, 2 to 4 gal (7.5 to 15 L) are required for 1 minute of operation. Because more water and solid waste are deposited in the sewer system, moreover, the central sewage treatment plant requires more energy to operate.

(b) Garbage Compactor

In some small buildings, this device allows for a much less bulky storage arrangement. Used selectively, it can compact several of the stacks of items

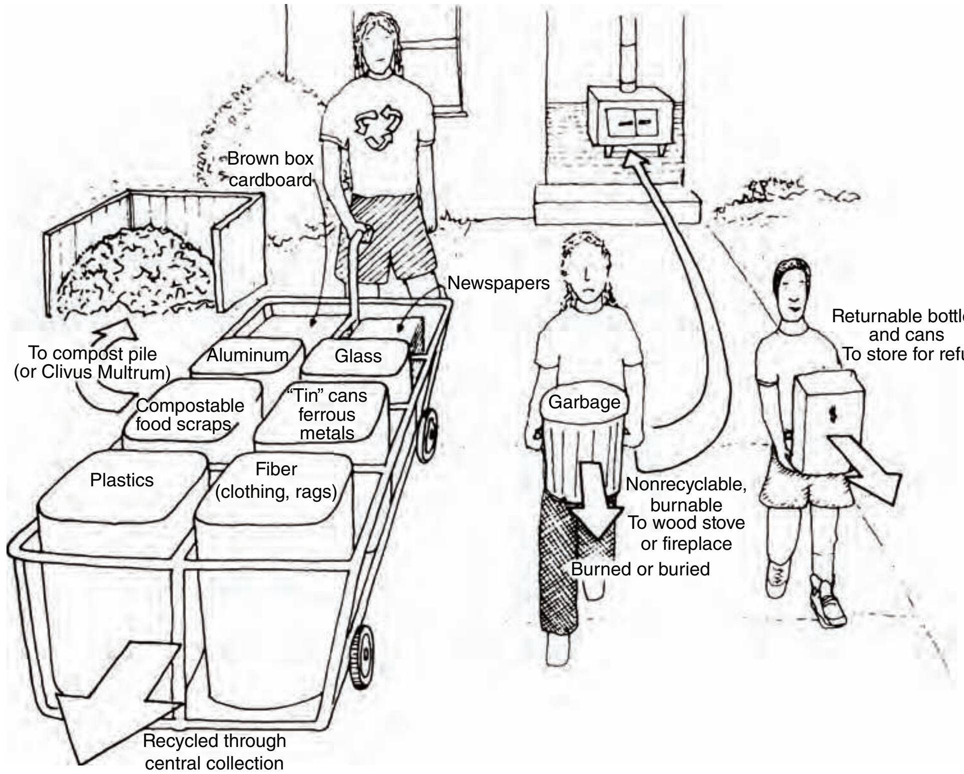


Fig. 21.2 *Local separation of solid wastes can require many containers. In communities that offer recycling garbage collection service, the consumer can recycle without transporting individual containers to many different collection points. Some recycling services ask for glass to be separated into green, brown, and clear types; some offer to recycle white paper separately from lower-grade paper.*

shown in Fig. 21.2, such as aluminum for recycling, ferrous metals, and box cardboard. Used indiscriminately, it can make the central process of garbage separation more difficult by crushing dissimilar items together. For a recycling-conscious single-family household, it is questionable whether a compactor will save much more storage volume than it takes for itself. However, small stores and institutions with large quantities of a bulky waste (such as cardboard) could save considerable storage space.

(c) Compost Pile

An alternative to a resource-hungry garbage disposal is the compost pile, familiar to most home gardeners as a source of excellent soil conditioners. Urban opportunities for composting seem very limited; however, raised growing beds on a balcony or window flower boxes are logical recipients of a family's compost. The problem may not be so much what to do with the final product (humus) as where to locate the compost pile. Several self-contained composting containers are commercially available.

The outdoor compost pile has several characteristics that challenge the designer. At its best, it is a frequently turned, quite warm, damp, well-aired source of rich humus (and red worms) for gardens; odors are noticeable only while the pile is turned. At its worst, it is a source of unpleasant odors, a breeding place for vermin, and a fast-food attraction for rats, dogs, and raccoons. Where odors are not objectionable, the heat generated in a frequently fed and tended compost pile might be welcome against the exterior walls of a residence. Clearly, these walls must have nonorganic exterior materials.

(d) Storage Areas

As groups of residences are combined into large apartment complexes, the necessary solid waste systems can make more significant demands on

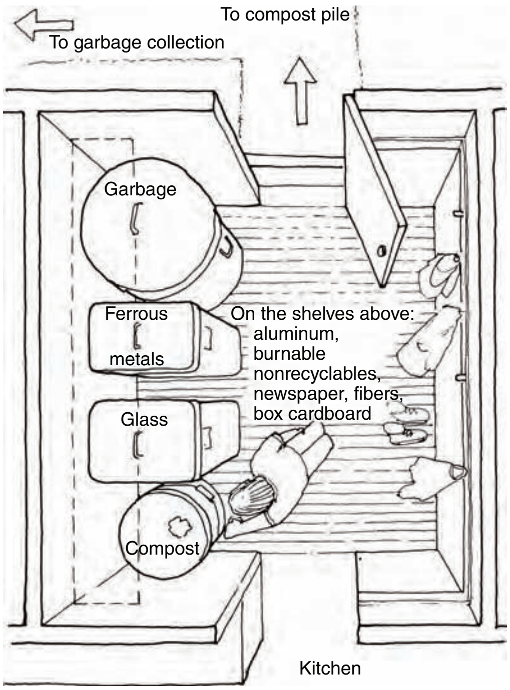


Fig. 21.3 *An entry vestibule (or air lock) to a kitchen can serve as a depository for solid wastes, as well as for coats, boots, and other items. Heavy, dirtier items belong on the floor, and many recyclables can be readily and conveniently stored on shelves. An outdoor hose bibb is useful for washing out soiled compost containers and garbage cans.*

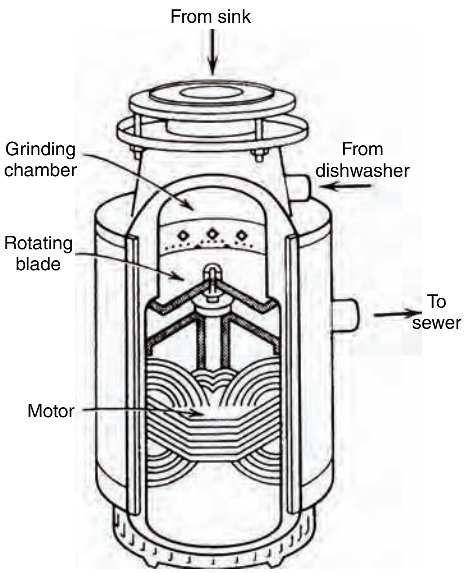


Fig. 21.4 *The garbage disposer (or grinder) diverts solid waste (food scraps) from landfills to sewage treatment plants. Occupying very little space, it saves garbage storage space and some of the user's time, but it requires more energy and much more water than treatment of the food scraps as garbage. Composting is another alternative. (From Milne, 1976.)*

the designer. Approximate exterior storage areas are listed in Table 21.3. Where central storage compounds are provided, garbage cans should be fenced to ward off dogs and other marauders. Different bins for recyclable materials might be provided. Where space is limited, a single bin could accept specific materials on designated days—newspapers on Mondays, metals on Wednesdays—if collection schedules permit. A central compost pile could provide humus for site landscaping. (An incinerator, used to recover heat from nonrecyclable burnable wastes, is almost never approved for installation today.) This combination of space and equipment has special environmental needs, including collection truck access, noise control, and location of both incinerator stacks and the compost pile with respect to prevailing winds.

21.4 SOLID WASTE IN LARGE BUILDINGS

In large buildings, it becomes more likely that solid wastes will be handled several times during the storage and collection process. This may inhibit the separated-waste approach because it is not only the employees who generate the waste, but also the custodians who collect and store it, who must understand what items go into which bins. Larger buildings, however, tend to generate large and concentrated kinds of wastes, which makes recycling more attractive, while also increasing the demand for storage space.

Consider the multistory office building. Office operations are likely to discard large quantities of white paper and smaller quantities of newspaper, box cardboard, and unrecyclable burnable trash (including floor sweepings). Much smaller quantities of food scraps (coffee grounds), metals, and glass are also generated. Given the high cost of floor space, the pressures are very high for a simple mixed-garbage can (rather than multiple separate bins). However, the cost of hauling trash to increasingly scarce landfills is now so high that many recycling programs can pay for themselves by avoiding landfill charges and by taking advantage of the value of recycled materials.

In larger buildings, the collection of solid waste is typically a three-stage process (Fig. 21.5). The first stage is the generation of the waste itself by employees who might be provided with one

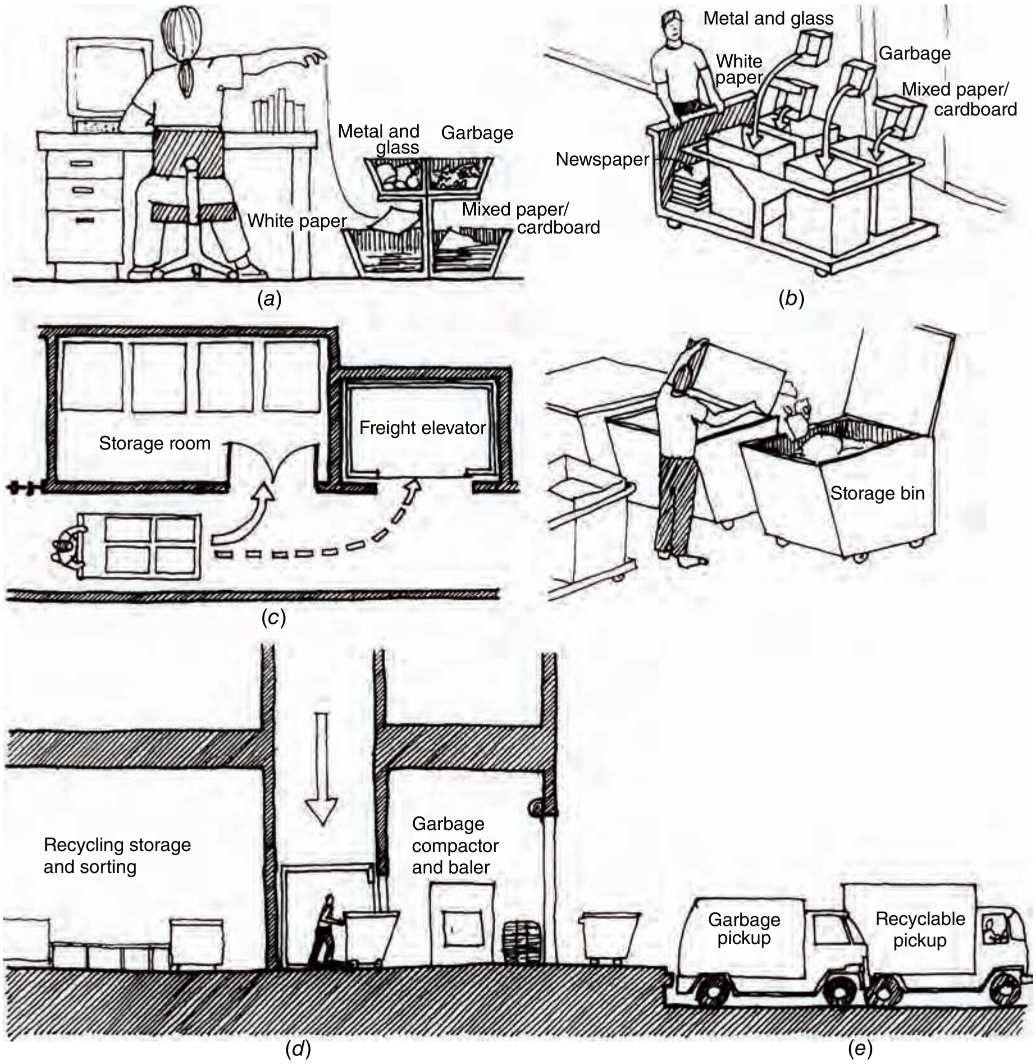


Fig. 21.5 Hypothetical three-stage solid waste collection process with four-category separation for office buildings. (a) At each workstation, a four-compartment waste receptacle is provided. White paper is the predominant waste product. (b) Custodians begin the second stage by collecting waste in separate bins. Floor sweepings are added to the garbage. (c) At the end of the second stage, the four categories of waste are deposited in separate bins. Service sinks, paper shredders, and other maintenance items can be incorporated in a service closet. (d) The third stage begins with compactors at the base of the service core. White paper is compacted, baled, and stored; recyclables are sorted and stored; garbage is compacted, baled, and stored. (e) At the end of the third stage, white paper, metal, plastic, and glass are collected for recycling, and garbage is collected for separation at a central plant.

wastebasket each. If each employee is expected to separate wastes, this suggests a redesigned receptacle. At the typical desk in an office building, white paper, recyclables, compostable materials, and garbage would be deposited in separate compartments. Waste separation at the point of origin thus may not require much more floor area, just more attention by the worker.

The second stage begins as custodians work with these individual baskets, dump them into separate bins on a collection cart, and reconnect the individual empty baskets for the next day's deposits. At various stations, special wastebaskets can be supplied: for white paper at the computer room and the copying machine, for compostable materials and garbage at the employee lounge. Floor sweepings are added to garbage. When the collection cart is full, it is wheeled to a service closet, which is probably located within the core of the building. Here there is a container for each category of waste, along with a service sink to wash out the garbage bin (and perhaps a paper shredder to be used selectively by employees).

The third stage begins at the ground floor of the service elevator, where: white paper and other recyclables are perhaps shredded and stored until collection; compostable materials are stored or sent to a roof garden compost pile; and garbage is compacted and bagged. In the storage space, a cool, dry, fresh air supply is desirable. A sprinkler (fire protection) system is often required. The compactors and shredders are noisy and must be vibration-isolated from the floor. At the end of the third stage, a truck or van from a recycling center collects recyclables, and a garbage truck collects garbage bags.

21.5 EQUIPMENT FOR THE HANDLING OF SOLID WASTE

One approach for the handling of solid wastes is to integrate multiple steel chutes of moderate diameter in the building's vertical core. Another approach is to use only one vertical chute, with a rotating receiving facility at the base (Fig. 21.6). With up to six receiving bins on a carousel and a control panel at each floor opening, considerable floor space is saved, compared to six individual chutes. (Also, custodial workers have fewer recyclables to separate and move.) The user first checks the control panel setting (it will be set at whatever bin the previous user had selected). After the user has made a selection, the carousel below turns to position the appropriate bin. The access panel then opens (interlocked so that only one floor can be opened at a time), and the recyclable material (or garbage) can be deposited. The receiving room at the base of the chute is about 12 ft (3.7 m) square, with a minimum height of 8 ft (2.4 m).

Where large amounts of solid waste are generated and little space is available in which to store it, various types of equipment can be used to change the volume or composition of the waste to facilitate its transportation and storage. The first step is to determine the probable daily flow of solid waste, as is done in Tables 21.1 and 21.2. When the extent of the problem is known, equipment can be selected.

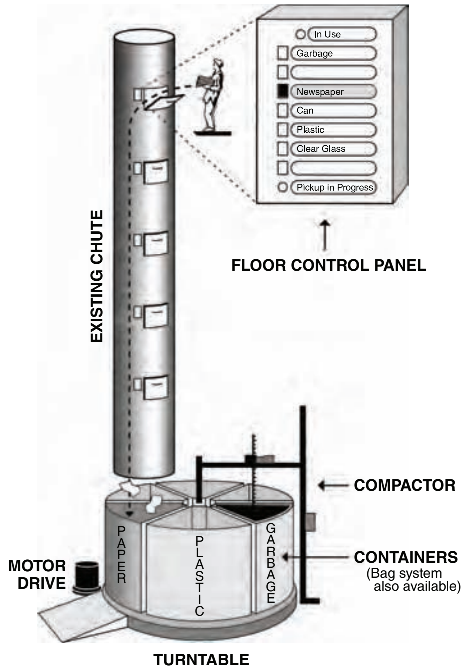


Fig. 21.6 One chute serves many different recyclables, as well as garbage, in this Hi-Rise Recycling System™. Interlocking access doors on each floor allow only one user at a time; the user selects the type of recyclable being deposited, using the control panel at the opening. (Courtesy of Hi-Rise Recycling Systems, Inc., Miami, FL.)

(a) Compactors

Of the wide variety of compacting devices (Fig. 21.7), most are able to reduce the volume of solid waste to as little as 10% of the original volume. Among the many choices to be made are: vertical versus horizontal compaction, automatic chute-fed versus manual free-standing, whether wastes are to be bagged or baled, and the final size of each unit of compacted waste. Compactors can be noisy; since heat is generated in the compaction process, they can also be prone to fires. Many compactors have built-in sprays for both fire control and disinfecting. Access to wash water and a floor drain are highly desirable.

(b) Vacuum Systems

The primary advantage of a vacuum system is that it reduces the building volume consumed by waste chutes or storage cans on each floor. A grinder-plus-evacuated-tube system is similar to

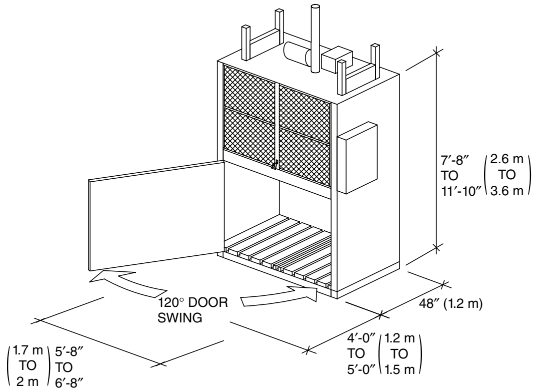


Fig. 21.7 *A refuse baler/compactor may save storage space where particular waste stream volumes are high. Cardboard, metal cans, and plastic bottles may be more attractive to recyclable haulers when their volume is thus reduced. (Reprinted by permission from AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *10th ed. © 2000 by John Wiley & Sons.)*

the vacuum sewage systems described in Section 19.7 (Fig. 19.49). Vacuum conveying systems are now used in several industrial applications, such as ash and wood-chip transporting. Vacuum systems that use air, not water, as the transport medium are frequently used for linens in hotels and for trash. Separate vacuum systems for trash and linens are desirable, both to lessen the soiling of the linens and to allow them to be delivered to a destination different from that for the trash.

The advantage of such pressurized systems is that lines can be small, and the contents can be moved horizontally or even up. This allows far greater flexibility in design than is possible with gravity systems.

(c) Summary

There are many options to be considered within the present waste-handling sequence of grind, crush, burn, and bury. As Earth's nonrenewable resources are stripped away, the recovery of materials from solid waste becomes increasingly attractive. The situation is similar to energy-and-design issues: After decades of energy-intensive building trends, designers are now allocating space to daylighting atria and allowing surfaces to act as thermal mass. A modest increase in floor space and equipment to encourage resource recovery from solid waste seems an increasingly worthwhile design investment.

21.6 THE SERVICE CORE

Medium- and high-rise buildings usually concentrate many building services within a core, from which services can be distributed as needed throughout each floor. The core typically contains stairs; passenger and freight elevators; toilet rooms; service closets; mechanical, plumbing, and electrical chases; electrical/telephone closets with local switching capabilities; fire protection equipment; and supply closets. The size of such cores varies widely; for example, the taller the building, the more elevators.

Often, these service cores are identical in plan from one floor to the next. Alternatively, the vertical services can be identical (stairs, elevators, chases) and the arrangement of other elements (toilet rooms, supply closets) allowed to vary. Whether or not minor floor-plan variations occur, the cores usually depart radically from the typical plan—and ceiling height—at both the roof and ground floor (Fig. 21.8). (Interruptions also occur where intermediate mechanical floors are provided.) Depending upon the type of elevator machinery selected, the machine room's ceiling height above the top floor being served might be three times the ordinary floor height (see Chapter 32). On the delivery/

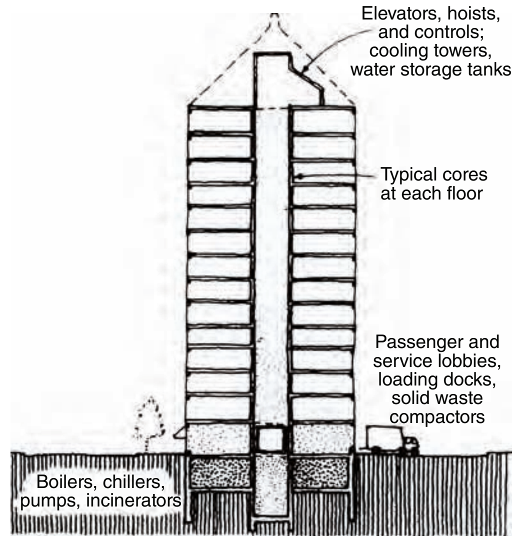


Fig. 21.8 *Schematic section through a core of a multistory building. At the top and bottom, floor space and ceiling height requirements increase. The consequences on the ground (or delivery/collection) floor are particularly great.*

loading floor level, large trucks must be accommodated. For chillers, boilers, incinerators, and fans, higher ceilings may be required to accommodate the flues, ducts, and pipes to which they must be connected; see Sections 12.5 and 12.7 for the dimensions required. Considering the entrance lobby as an extension of the core, a building's service core can expand to nearly fill the ground floor. This core expansion typically happens on the roof and in the basement as well.

A service core can be related to the remaining service floor area in any of several ways (Fig. 21.9). Common arrangements are: a single central core or one that is detached, two cores symmetrically placed, corner cores, or core services dispersed somewhat randomly.

Each core location has advantages and drawbacks. From the viewpoint of rentable space, important factors are: the flexibility of the served (rental) floor area; the exposure of rental area to

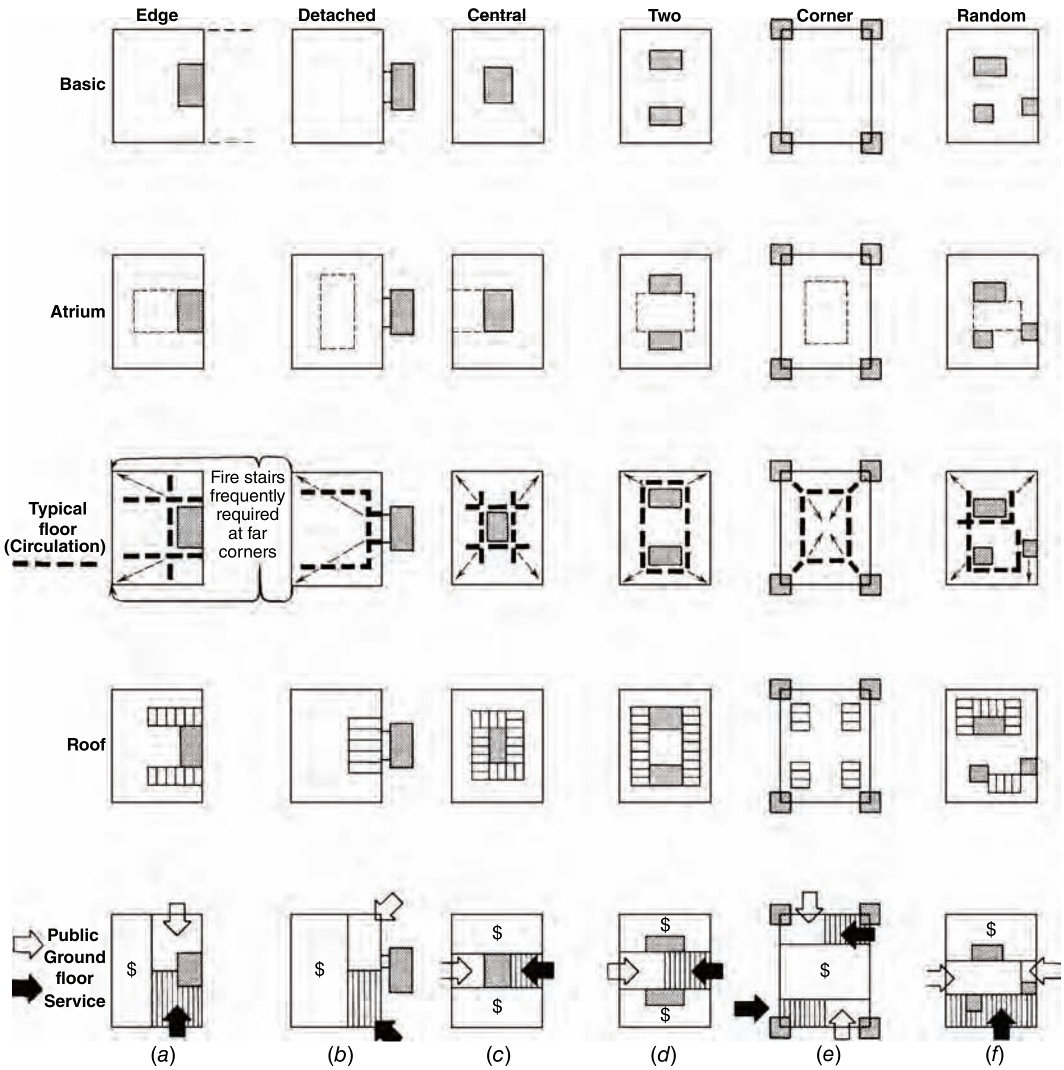
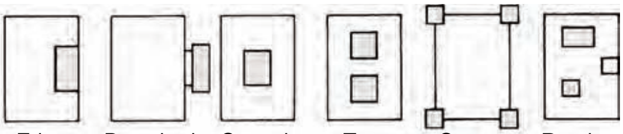


Fig. 21.9 Comparison of core arrangements and building plans. (a, b) The edge and the detached cores give great flexibility to the rental floor area, with light and view for core spaces. (c) The central core expands readily at the roof and the ground floor, and has clear circulation and fairly flexible rental space. (d) Two-core is a popular, workable arrangement. (e) The corner cores give great flexibility to rental floors but are difficult at the roof and ground floor. (f) Random cores generally occur in low-rise buildings, in which the benefits of repetitious plans are minimal.

TABLE 21.4 Building Characteristics and Core Placement

Core designs



Core designs	Edge	Detached	Central	Two	Corner	Random
Flexibility of typical rental areas	Good	Excellent	Average	Fair	Good	Poor
Perimeter for rental areas	Fair	Average	Excellent	Excellent	Poor	Good
Ground-floor high-rent area	Average	Excellent	Average	Fair	Good	Poor
Distance of travel from core, typical	Fair	Poor	Good	Excellent	Average	Average
Clarity of circulation, typical	Average	Fair	Good	Excellent	Average	Poor
Daylight, view for core spaces	Good	Poor	Excellent	Poor	Excellent	Fair
Core expansion at roof	Average	Excellent	Excellent	Good	Fair	Average
Core expansion at ground floor	Average	Fair	Good	Excellent	Poor	Average

Excellent Good Average Fair Poor

the perimeter, and thus to light, air, and view; and the extent to which ground-floor high-rent space gets commercial exposure. For fire safety and occupant convenience, the distance of travel from the farthest rental floor area to the service core, and the clarity of circulation within the rental area, are important. For the environment within the core—toilet rooms, stairs, elevator waiting areas—access to light, air, and view is desirable. For the mechanical services, ease of core area expansion on the roof, at the loading dock, and in the basement is important, as is the length of travel for ducts and other such elements within each floor. These factors are compared for various types of core designs in Table 21.4.

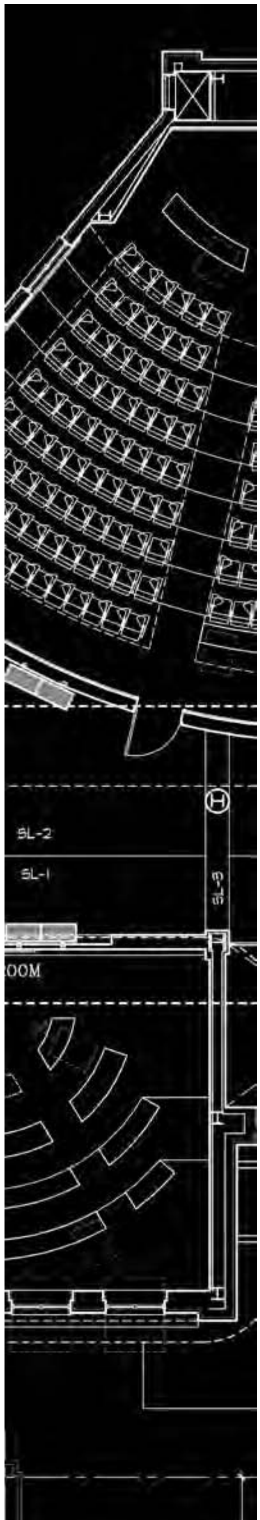
References and Resources

AIA: Ramsey/Sleeper. 2000. *Architectural Graphic Standards*, 10th ed. John Wiley & Sons. New York.

Milne, M. 1976. *Residential Water Conservation*. U.S. Office of Water Research and Technology, Department of Commerce, NTIS. Springfield, VA.

PART V

ACOUSTICS



The distinction between the terms *sound* and *noise* is a subjective one—sound is desirable, noise is not. This differentiation does not consider the specific content of an acoustical signal. For example, speech, which is a desirable sound in most instances, can become noise when coming from a neighbor's apartment at 2:00 A.M. or from an adjoining office. An air-handling unit, which is often considered a noise producer, can in some situations provide a desirable sound that can mask intruding speech (noise). The function of architectural acoustics is simply to follow this logic: to enhance desired sounds and to attenuate noises.

It is important to note that there is no unified theory of acoustical comfort, such as is available to guide design efforts dealing with thermal comfort. Design for good acoustics involves addressing a number of acoustical issues correctly—but individually. What is missing is a holistic view of how changing one acoustic parameter (say, reverberation time) will affect the design criteria for another variable (such as sound pressure level). In the context of such integrated systems, it becomes the designer's job to qualitatively balance the interactions between acoustic properties of spaces when establishing design intent and criteria.

Chapter 22 introduces the subject of architectural acoustics, along with a discussion of physical sound theory and physiological hearing phenomena. The latter include the negative effects of noise—that is, the primarily psychological impressions (involving annoyance) at low levels of noise, up to the hearing damage produced at high levels of noise. The chapter provides a description of the types of sounds typically encountered in architectural spaces, and the criteria for acceptable background noise levels in indoor spaces. These are expressed as noise criteria (NC) and room criteria (RC) curves.

Chapter 23 covers room acoustics—with an explanation of absorption and reverberation, and develops acoustic design criteria for various indoor activities. The chapter concludes with a description of sound reinforcement systems.

Chapter 24 is devoted to noise control. It begins with a discussion of the use of absorptive materials for room noise reduction. It treats the problem of interspace noise conduction, dividing the problem into two parts (airborne noise and structure-borne noise) because the solutions are different. Relevant criteria, including sound transmission class (STC) and impact isolation class (IIC), are introduced and explained, and solutions to noise transfer problems of different types are suggested. The problem of speech privacy for both enclosed spaces and open (often office) areas is treated in detail. The chapter offers information on mechanical system noise control and acoustic recommendations and criteria, ending with a discussion of exterior acoustics. Acoustical reference information is also provided.

CHAPTER 22

Fundamentals of Architectural Acoustics

THE ACOUSTIC ENVIRONMENT PLAYS AN IMPORTANT role in supporting (or disturbing) an overall sense of comfort in many of the spaces we occupy on a daily basis—including both residential and commercial/institutional spaces. For several reasons, many design solutions seem to shortchange the acoustical environment. This is partly due to the perceived complexity of architectural acoustics, partly due to lack of coverage of the topic in many architecture programs. Good acoustics is not required by most building codes and is not a key element in the majority of green building rating systems. Nevertheless, providing acceptable acoustical conditions is a fundamental part of good design practice.

22.1 ARCHITECTURAL ACOUSTICS

Architectural acoustics may be defined as the design of spaces, structures, and mechanical/electrical systems to meet hearing needs. With proper design efforts, wanted sounds can be heard properly and unwanted sounds (noise) can be attenuated or masked to the point where they do not cause annoyance. Achieving good acoustics, however, has become increasingly difficult for a variety of reasons. To lower construction costs, the weight of various materials used in many of today's buildings has been reduced from those prevalent 50–100 years ago. Since light structures generally transmit sound more readily than heavy ones, lightweight buildings have the potential for major acoustical problems. Population density in office spaces has steadily increased, thus increasing the amount of noise generated, and decreasing the distance between occupants. Worse yet—from the acoustics point of view—many offices today are designed as open areas with, at best, only thin, partial-height dividers (cubicles) separating workers. Forty percent or more of a building budget may be allocated for mechanical systems—most of which generate noise. Outside noise sources, such as cars, trucks, trains, and airplanes, can also present problems and require isolation of interior spaces from exterior sounds. This is particularly problematic where natural ventilation is used.

Building owners and tenants are aware that quality acoustic environments are required for high productivity and comfort in buildings, and hence for competitive rental or resale values. The architect is expected to provide such acoustic quality. A clear understanding of the principles explained in this and the following chapters will assist the architect in preparing straightforward designs, alone and, in more complex instances, by knowledgeable collaboration with an acoustic consultant. Proper acoustic design responses early in the design process are critically important, since after-the-fact acoustic "repair" is often difficult (and, therefore, costly) and sometimes impossible without substantial structural alterations (which are very costly).

All acoustical situations have three common elements—a sound source, a sound transmission path or paths, and a receiver of the sound. Through design, a source can be made louder or quieter, and a path can be made to transmit more or less sound. Working with sources and paths throughout the various design phases (and into construction and often into occupancy) is the bread and butter of architectural acoustics. The listener's perception of sound also may be influenced, although this is not normally an "architectural" solution. This chapter presents the fundamental bases of architectural acoustics to assist a designer in defining appropriate acoustic intents and criteria. Moreover, it describes basic methods for reaching such intents through the design process.

22.2 SOUND

Sound can be defined in a number of different ways, depending upon the aspect of most interest or concern. It can be described as a physical wave, or as a mechanical vibration, or simply as a series of pressure variations in an elastic medium. For airborne sounds, the medium is air. For structure-borne sounds, the medium may be concrete, steel, wood, glass, or combinations of these materials. A much more limited definition of sound, more appropriate to architectural acoustics, is that it is simply an audible pressure variation. This establishes that architectural acoustics is concerned with the building occupant. It also suggests that there may be accoustical pressure variations that cannot be heard. This is the case with *vibration*, which is a pressure variation that can be felt but not heard.

(a) Speed of Sound

Sound travels at different speeds, depending upon the medium. In air, at sea level, sound velocity is 1130 fps (344 m/s). This is 770 miles per hour (1239 kilometers per hour)—slow when compared to light, which has a speed of 186,000 miles per *second* (299,338 km per second). Since sound travels not only in air but also through parts of a structure, it is of interest to know the speed of sound in other media

TABLE 22.1 Speed of Sound Propagation in Various Media

	Speed	
Medium	**Meters per Second**	**Feet per Second**
Air	344	1130
Water	1410	4625
Wood	3300	10,825
Brick	3600	11,800
Concrete	3700	12,100
Steel	4900	16,000
Glass	5000	16,400
Aluminum	5800	19,000

Note: These figures are approximate, since the listed materials vary in density. An average frequency is assumed.

(Table 22.1). For architectural design purposes, speed variations due to changes in temperature and altitude (atmospheric pressure) may be ignored, and for most calculations, 1130 fps (344 m/s) may be used as the speed of sound in air (usually within 3% error). From a practical standpoint, the speed of sound in air is slow enough that the travel time of a sound signal can be a key design issue.

(b) Wavelength

The *wavelength* of sound is defined as the distance between similar points (peaks or troughs) on successive waves, which is the distance sound travels in one cycle. The relationship between wavelength, frequency, and speed of sound is expressed as

$$\lambda = \frac{c}{f} \tag{22.1}$$

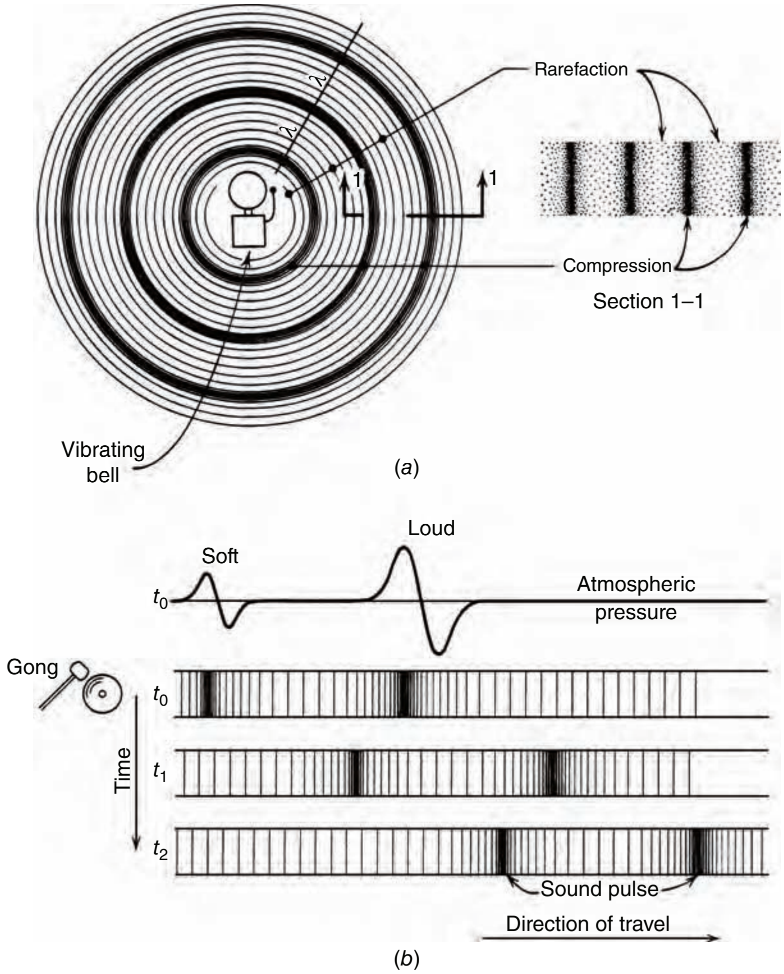
where

λ = wavelength, ft (m)
c = velocity of sound, fps (m/s)
f = frequency of sound, Hz

Low-frequency sounds are characterized by long wavelengths, and high-frequency sounds by short wavelengths. Sounds with wavelengths ranging from 0.5 in. to 50 ft (12 mm to 15 m) can be heard by human beings. A simple nomograph (see Fig. 23.18) permits rapid determination of wavelength, given sound frequency, and vice versa.

(c) Frequency

The number of times that a cycle of compression and rarefaction occurs in a given unit of time is described as the *frequency* of a sound. For example, if there are



Interactive Animation

Fig. 22.1 *Sound pressure waves. (a) The continuous vibration from the bell causes a series of compressions and rarefactions of the air to travel outward longitudinally from the source. Amplitude information is carried by pressure; that is, greater amplitude means greater compression and greater rarefaction. (Compression and rarefaction are shown diagrammatically as line density, although they are actually molecular phenomena, as shown in the upper drawing.) (b) Two single impulses of different magnitude (amplitude) traveling away from the source. Note how amplitude information is carried by the difference in pressure.*

1000 such cycles per second (cps), the frequency of the sound is 1000 cps—1000 hertz (Hz) in standard nomenclature. Thus, in Fig. 22.1, higher frequencies would be shown by compressions and rarefactions that are closer together, and lower frequencies by those that are farther apart. In architectural acoustics, frequency is sometimes referred to using a term borrowed from music—*pitch*. The higher a sound's frequency, the higher its pitch, and vice versa.

Sound frequency is integrally linked to speech and hearing. The approximate frequency range of a healthy young person's hearing is 20 to 20,000 Hz. The human speaking voice has a range of approximately 100 to 600 Hz in *fundamental frequencies*, but *harmonics* (overtones) reach to approximately 7500 Hz. Most speech information is carried in the upper frequencies, whereas most of the *acoustic energy* exists in the lower frequencies. The critical frequency range for speech communication is 300 to 4000 Hz. Overtones outside these core frequencies, however, give the voice its characteristic sound and specific identity (Fig. 22.2).

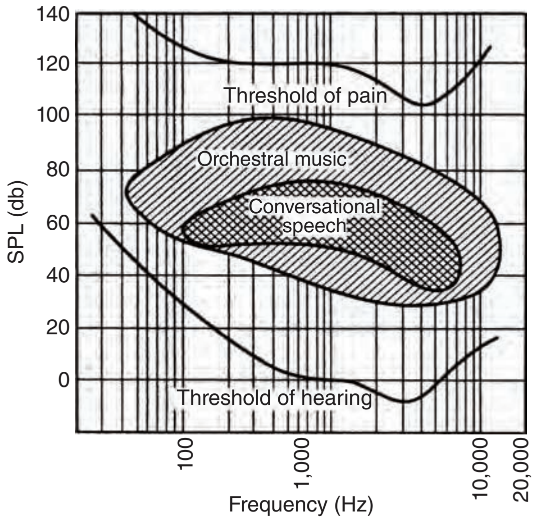


Fig. 22.2 The positions of speech and wide-range music in the aural field of the human ear are illustrated. Speech is in the nominally linear response area of the ear, as is most music. Beyond these frequencies, the ear effectively attenuates the incoming signal.

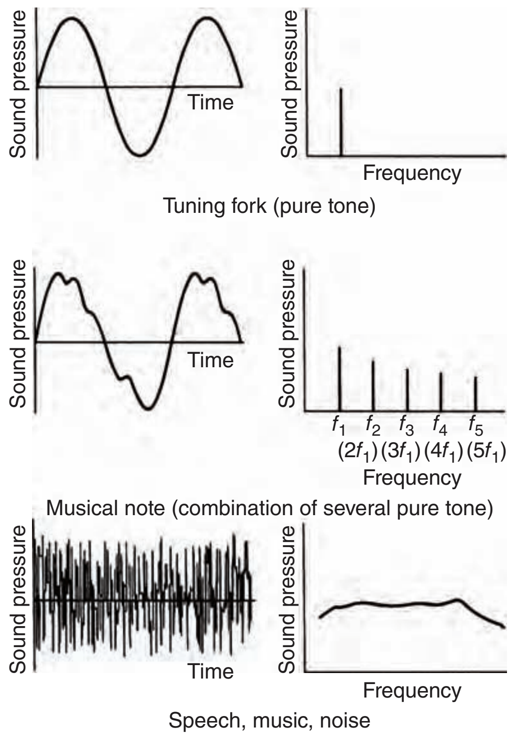


Fig. 22.3 Schematic representations of a pure tone, a musical note, and a more complex sound (such as speech, music, or noise), showing the variation of sound pressure with time and frequency.

A sound composed of only one frequency is called a *pure tone*. Except for the sound generated by a tuning fork, few sounds are truly pure. Musical sounds (tones) are composed of a fundamental frequency and integral multiples of the fundamental frequency (harmonics). Most common sounds are complex combinations of frequencies. Figure 22.3 shows examples of pure tones, musical notes, and common sounds, while Fig. 22.4 shows the frequency ranges of some common devices and phenomena. Telephone and radio communication are accomplished using a considerably narrower frequency band by sacrificing some voice quality and intelligibility.

(d) Octave Bands

The frequencies in the scale of Fig. 22.4 all stand in the ratio of 2:1 to each other—that is, 16:32:63:125:250, and so on. Borrowing again from musical terminology, they are one *octave* apart. These particular frequencies are also accepted internationally as the center (reference) frequencies of octave bands used for the purpose of sound specification. For technical reasons, a geometric mean is used. Thus, 250 is the center frequency of an octave band ranging from $250/\sqrt{2}$ to $250\sqrt{2}$, with that particular octave being known as the *250-Hz octave*. If a finer division is required for analysis purposes (unusual in architectural acoustics), ½-octave and ⅓-octave bands are used. Because frequency is so important to architectural acoustics, and because there are 19,980 discrete whole frequencies in the normal range of hearing, octave bands are used repeatedly during design as a way of capturing frequency-specific information about sounds without becoming buried in detail.

(e) The Concept of Sound Magnitude

The magnitude of a sound signal is a relatively complex concept because there are a number of different metrics (and associated terminology) in common use and because of the great range of values involved in day-to-day acoustic situations. Sound magnitude is often equated with loudness, which is a subjective, receiver-oriented response not linearly related to the power of a sound (in watts). The physical magnitude of sound is variously described as

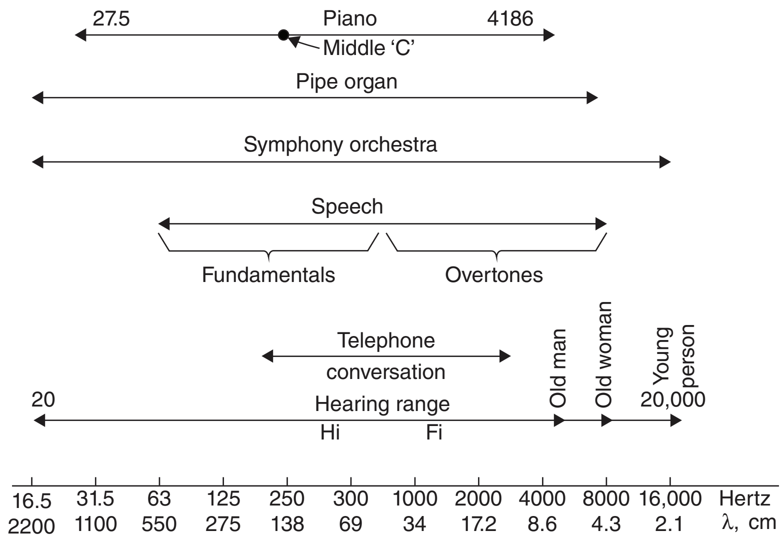


Fig. 22.4 *Frequency ranges of common instruments. Wavelength (λ) is calculated on an assumed propagation velocity of 344 m/s (1130 fps).*

sound power, *sound power level* (PWL), *sound pressure*, *sound pressure level* (SPL), *sound intensity*, and *sound intensity level* (IL). Each of these metrics has a place, and each differs from the others and from subjective loudness. To clearly understand these concepts—and it is imperative that they be understood—a comprehension of how we hear and how sound is propagated in free space is necessary.

(f) Sound Propagation

For simplicity, it is probably best to view sound as a series of pressure variations. In air, these pressure variations take the form of periodic compressions and rarefactions. The bell in Fig. 22.1 radiates a tone in all directions equally—that is, it creates a circular wavefront. As the material of the bell vibrates, it sets up vibrations of the same frequency in the air, which can best be visualized in a sectional view. Notice that the pressure changes containing the sound information travel in the same direction as the wavefront—longitudinally. Sound is therefore a *longitudinal* wave motion. This is unlike (for example) an AM radio signal, in which the wave travels longitudinally, but the information—that is, the modulation—is transverse. Sound is a mechanical wave, whereas light and electricity are electromagnetic waves.

22.3 HEARING

As noted in Section 22.2(c), the approximate frequency response of a healthy young person's hearing is 20 to 20,000 Hz. The upper limit decreases with age as a result of a process called *presbycusis* (Fig. 22.5). The loss is more pronounced in men than women. Recognition of this phenomenon can be of importance in schools, since very high-pitched sounds that are inaudible to most adults can be a source of extreme annoyance to young students. For example, dentists report that high-speed drills and tooth-cleaning devices cause extreme auditory discomfort in many young patients. These devices produce sounds in the 15- to 20-kilohertz (kHz) range.

(a) The Ear

Referring to Fig. 22.6, the outer ear is funnel-shaped and serves as a sound-gathering input device for the auditory system. Sound energy travels through the auditory canal (outer ear) and sets in motion the components of the middle ear, comprising the eardrum, hammer, anvil, and stirrup. The stirrup acts as a piston to transmit vibrations into the fluid of the inner ear. The motion of this fluid causes movement of hair cells in the cochlea, which, in turn, stimulates nerves at the bases of the hairs.

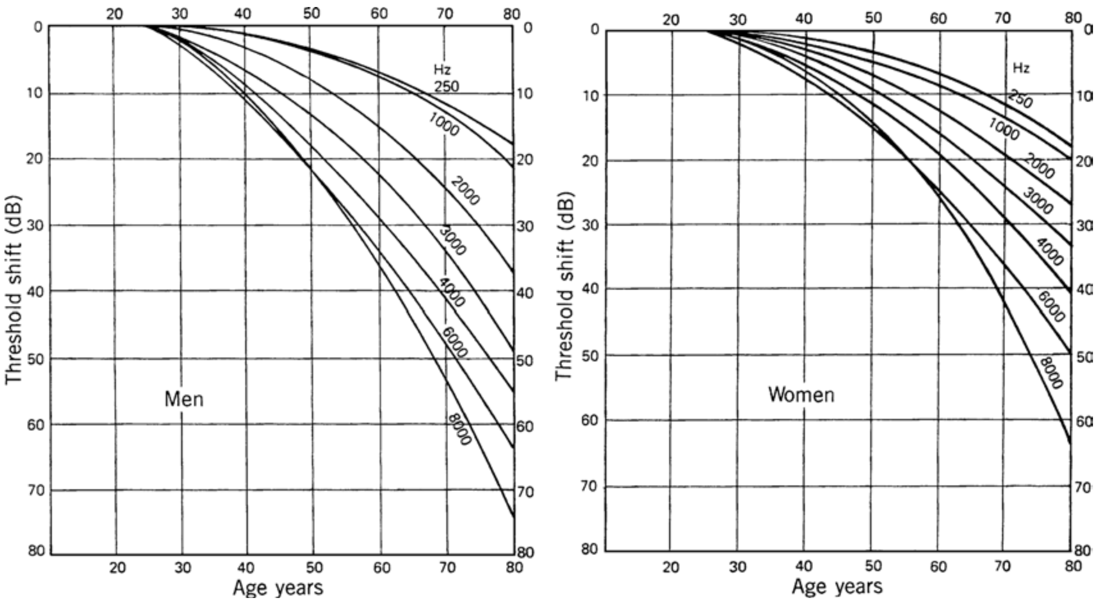


Fig. 22.5 *These curves illustrate the average hearing threshold shift for men and women with increasing age, relative to a 25-year-old reference group. Note that at age 60 the male threshold shift at upper speech frequencies (4000 Hz) is 30 dB, compared to 20 dB for women, a difference of 10 dB or one-half of the subjective loudness (see Table 22.2). For men older than 50 and women older than 60, frequencies above 10 kHz are effectively inaudible, and even at normal speech frequencies of 1000 to 2000 Hz, subjective loudness is reduced to one-half of that of a 25-year-old listener. (Reproduced with permission from F. A. White. 1975.* Our Acoustic Environment. *John Wiley & Sons, New York.)*

The nerves, in turn, transmit electrical impulses along the eighth cranial nerve to the brain. These impulses we understand as sound.

It is often assumed that the ear ignores phase differences and combines frequencies. This may not always be the case, however, particularly when the frequencies are very far apart. For this reason, a single-number representation of a complex sound (the type of information found in Table 22.4) can be misleading and must be used with caution.

At the threshold of hearing (approximately 0 dB), the displacement of air molecules impinging on the eardrum, and the eardrum excursion, are approximately one angstrom unit (1 Å = 10^{-8} cm), which is approximately the diameter of an atom. Were the ear an order of magnitude more sensitive, it would hear thermal noise. The human ear is thus operating close to the practical limit of sensitivity. At the other end of the magnitude spectrum, the threshold of pain corresponds to a sound pressure level of 130 dB and to an eardrum motion of approximately 0.25 mm (0.01 in)—truly an astonishing range.

TABLE 22.2 Intensity Level Changes and Corresponding Subjective Loudness Changes

Change in Intensity Level (dB)	Subjective Change in Loudness
3	Barely perceptible
6[a]	Perceptible
7	Clearly perceptible
10	Twice (or half) as loud
20	Four times (or one-quarter) as loud

[a]Six decibels corresponds to the change encountered when the distance to the source in a free field is doubled (halved).

A number of "measures" of sound magnitude are encountered in architectural acoustics. Movement of the eardrum (and thus hearing) is caused directly by air pressure variations. Therefore, the physical magnitude generally of most interest to architectural acoustics is sound pressure (*force density*), and its derivative—sound pressure level—which is the ratio of a given sound pressure to a base level, expressed in decibels.

(b) Equal Loudness Contours

The human ear is not uniformly sensitive over its entire frequency range of 20 Hz to 20 kHz. The

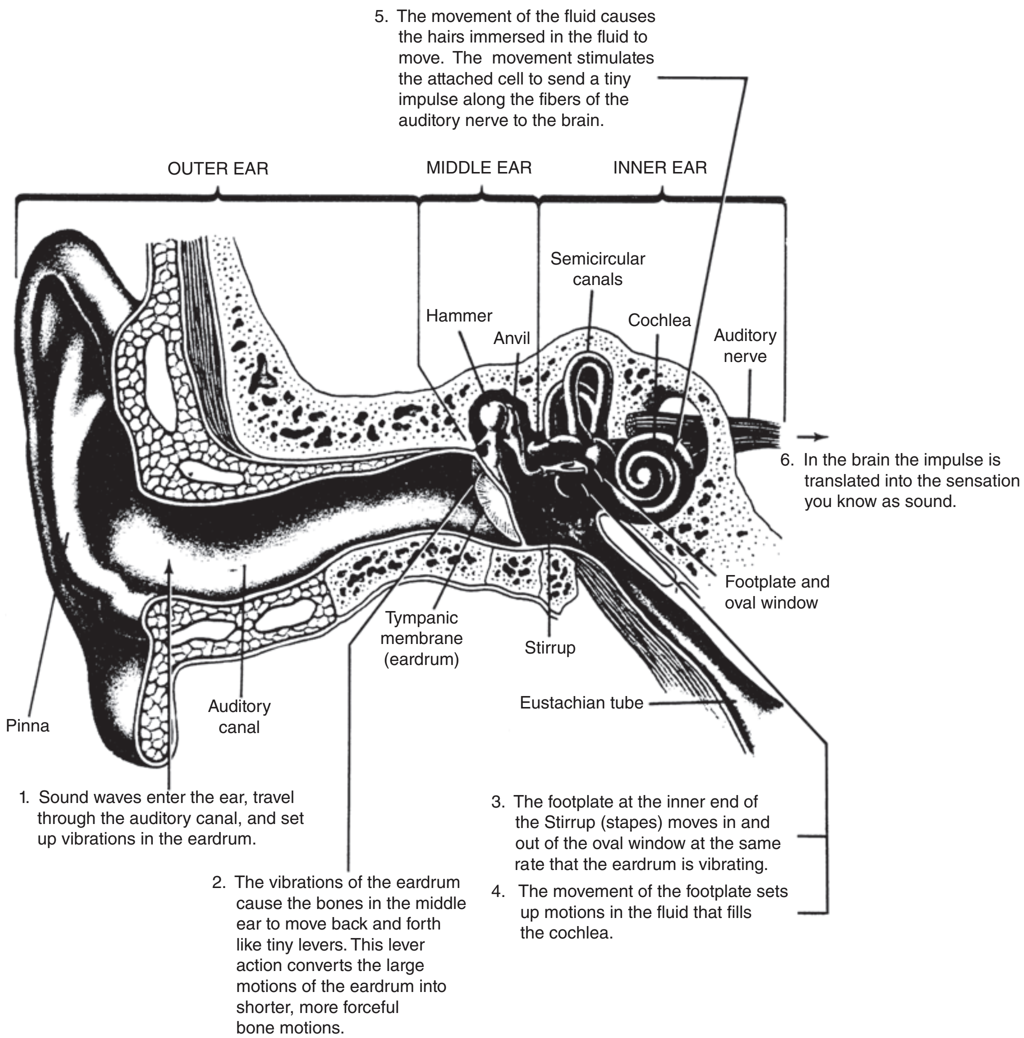


Fig. 22.6 *Drawing of the human ear showing the principal parts and its function as a sound receptor. (Drawing reproduced with permission from F. A. White. 1975.* Our Acoustic Environment*. John Wiley & Sons, New York. Notes are reproduced from* Quieting: A Practical Guide to Noise Control*. NBS. 1976.)*

120- to 130-dB upper limit (pain threshold) occurs at all frequencies. At the lower limit, however, the 0-dB threshold occurs only at 1000 Hz. The ear is in fact most sensitive at 3000 to 4000 Hz, at which frequencies the threshold is about −5 dB (relatively speaking). This type of nonlinear response exists throughout the ear's hearing range. To determine the nature of this nonlinearity, a large number of tests were conducted with pure tones of different frequencies, in which listeners were asked to equate the subjective loudness of signals. These test results produced a family of curves called *equal loudness level contours* (sometimes called *Fletcher–Munson equal loudness contours* after two of the principal researchers). These curves (Fig. 22.7) are internationally recognized and standardized, and are used as the reference for normal hearing response. They are also used to "weight" measuring devices, as explained later in this chapter. Note that *by definition*:

1. All points on a single contour have the same *subjective* sensation of loudness.
2. The loudness level in *phons* (the number shown in the center of each curve in Fig. 22.7) of the *entire* contour is defined by the decibel level of that contour at 1000 Hz.

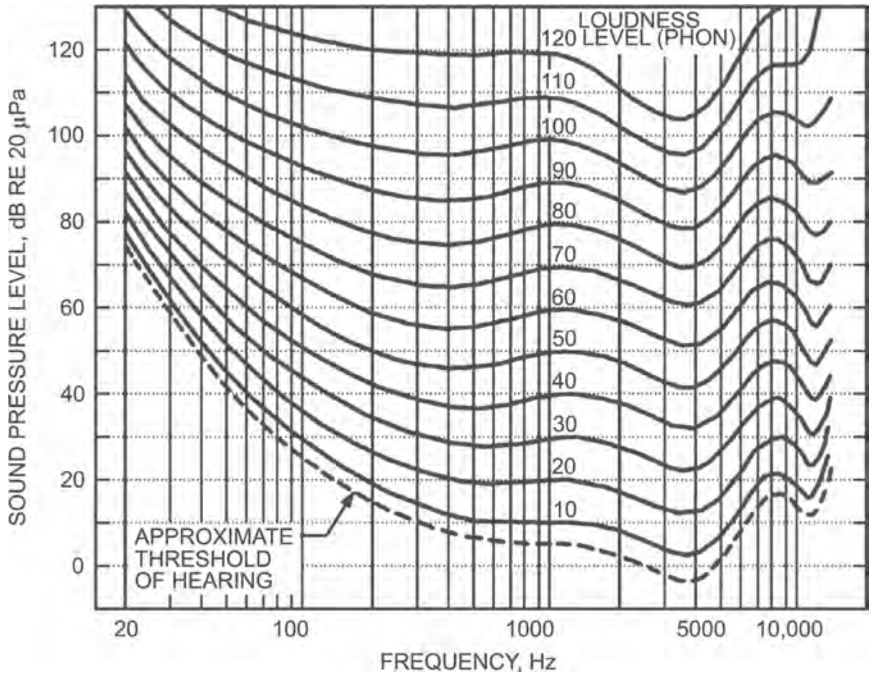


Fig. 22.7 *Standard equal-loudness contours. These curves are accurate for a listener with normal binaural hearing situated in the near field of a source producing pure tones directly ahead of the listener. The subjective (perceived) loudness of each contour is quantified in a unit called the phon. The phon value of each curve is shown in the center of the figure. Note that a sound pressure level of 60 dB corresponds to 30 phons at 50 Hz, 50 phons at 100 Hz, 63 phons at 500 Hz, 60 phons at 1 kHz, 68 phons at 4 kHz, and 60 phons at 6 kHz. This indicates the relative flatness of the ear's response in the central frequency range and the sharp drop at low frequencies. (Reprinted with permission; ©ASHRAE, 2013* ASHRAE® Handbook of Fundamentals.*)*

The phon scale was constructed as a way of defining perceived sound (subjective loudness impressions) in terms of the ear's nonlinear response. Assigning a single number—in a unit called the *phon*—to an equal loudness contour makes it possible to compare subjective loudness impressions of two sounds, regardless of frequency or actual sound pressure level. Thus, in Fig. 22.8, the subjective loudness of a whisper in the ear (20 phons) is the same as that of distant pounding surf, despite the fact that the sound pressure level (SPL) of the former is 20 dB and that of the latter is 80 dB. The 60-dB differential is due to the ear's sharp drop in sensitivity at low frequencies. However, because the phon scale is nonlinear in terms of perceived loudness (a given phon differential does not correspond to the same perceived loudness change throughout the phon scale) and because phons cannot be combined arithmetically to give a resultant subjective loudness (60 phons plus 50 phons is *not* 110 phons), the scale has found few uses (one of which is to rate the noisiness of bathroom fans).

The Fletcher–Munson contours demonstrate some interesting phenomena:

1. Sensitivity drops off sharply at low frequencies, particularly at low dB levels. (For this reason, most stereo amplifiers provide automatic bass boost at low volume levels.)
2. Maximum sensitivity occurs between 3 and 4 kHz—precisely the frequencies that convey the most information in human speech (see Fig. 22.2).
3. In a normal listening range of 45 to 85 dB, and in the most often used frequency range of 150 Hz to 6 kHz, the contour is substantially flat; that is, the ear's response is effectively linear in this zone. It is only at extremes of sound level and frequency that nonlinearity occurs.

The ear "averages" sounds over a minimum time increment; sound impulses of shorter duration will be perceived as quieter than they would if received as a steady-state sound. This minimum sound pulse length (i.e., the time required for the

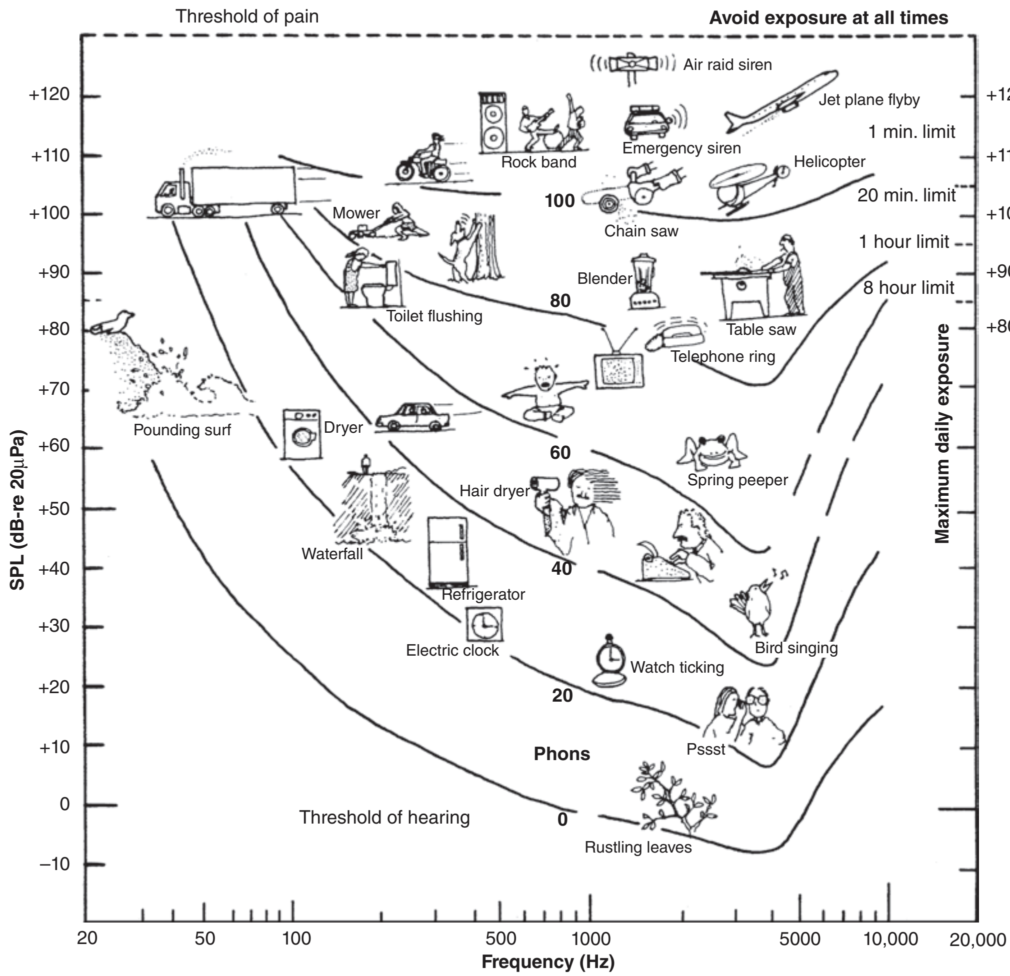


Fig. 22.8 *Common sound sources plotted at their dominant frequencies and levels as typically heard by the observer. The equal-loudness contours (see Fig. 22.7) show why certain sounds seem louder than others, despite the pressure levels that would indicate the contrary. (Reprinted with modification from* Quieting: A Practical Guide to Noise Control*, NBS. 1976.)*

sound to achieve full loudness) varies within the range of 50 and 200 milliseconds (ms) (1⁄20 to 1⁄5 s) and depends to an extent upon the frequency content of the sound. The figure of 70 ms (1⁄14 s) is frequently found in the literature. This threshold time becomes important when considering the effect of echoes (see Sections 23.11–23.14).

(c) Masking

When two separate sound sources are perceived simultaneously, the perception of each is made more difficult by the presence of the other. This effect is known as *masking*, which is defined technically as the number of decibels by which the threshold of audibility of one sound is raised by the presence of another sound. The masking effect is greatest when two sounds are close in frequency or frequency content, since the ear has greater difficulty separating like frequencies. Also, a low frequency will mask a high frequency more effectively than the reverse for the same decibel levels. With broad-frequency sounds, the masking effect is difficult to predict, since it depends in part upon how intently a listener is listening. Masking is an extremely important and useful technique for noise control, wherein background sound levels are deliberately manipulated to mask other unwanted sounds (see Chapter 24 for details). The background sounds used for this purpose are of a broadband continuous nature, such as "pink" noise and are non-information-bearing. They serve to depress the intelligibility of lower-magnitude, information-bearing sounds that would otherwise cause annoyance, and are particularly useful in open (landscaped) office plans where few noise control alternatives exist. Frequently, mechanical equipment sound (such as that from air diffusers and fans) can be utilized to good advantage as masking sound.

(d) Directivity

The exact mechanism by which the binaural aspect of hearing detects direction is not entirely understood. It is clear, however, that the brain can sense the direction of a sound source in many environments. In enclosed spaces, echoes from surface reflections (reverberation) will blur most directivity, and any "stereo" information will be almost completely dependent upon high frequencies in the near field (the sound field that is close to the source and therefore minimally affected by reverberation). Since high frequencies (with short wavelengths) travel in a relatively straight line, they will reach a listener before their reflections, and in so doing will cue the hearer as to their origin. Low frequencies (and thus long wavelengths) are difficult to localize, however, because the wavelengths are large compared to the dimension between our ears. Low frequencies, even in the near field, are readily mixed with their reflections, thus confusing the location of their origin.

(e) Discrimination

Frequency recognition is accomplished in the cochlea by the hair cells embedded in the basilar membrane. The human auditory field spans the frequencies between 20 Hz and 20 kHz, although the threshold of sensitivity is different at each frequency. The ear can hear and recognize distinct frequencies, yet the hearing mechanism has the ability, apparently as directed by the brain, either to hear individual frequencies or to combine them into a single more complex sound. Thus, when we hear a string quartet we can, generally *at will*, hear either the entire quartet or each instrument individually. With concentration (vision helps in this regard), a trained ear can pick out a single instrument in an orchestra of 120 pieces, even if there is more than one such instrument in the same section. Conductors do this regularly. Similarly, the ear can perform the discrimination feat known as the cocktail party effect, that is, pick out one voice among background sounds that may be substantially louder than the wanted signal. In effect, the ear in this case attenuates the unwanted sound signals. Normally, however, the ear does precisely the opposite. It combines sounds that are clearly distinct from each other in frequency and phase. The three tones in a chord struck on a piano are different in frequency and, if played as a very rapid triplet, out of phase. Yet the ear combines them and hears a single sound, despite the fact that the maxima of the three tones do not occur simultaneously.

22.4 SOUND SOURCES

Building occupants encounter a wide range of sounds in the course of a day. Some of these sounds are produced by human beings, others by mechanical equipment or natural phenomena. Some of the sounds are information-bearing, while others convey nothing intelligible. Speech and music are sounds of particular interest to building designers, as are those sounds deemed to be noise.

(a) Speech

As can be seen from Fig. 22.2, the ear's sensitivity is highest in the speech frequency and the normal energy range. Individual speech sounds vary in duration between 30 and 300 ms, and the ear normally perceives these individually and clearly. Speech is composed of *phonemes*, which are individual and distinctive sounds that, to an extent, vary from language to language. Certain phonemes exist in one language and not in another. Since some phonemes carry more information than others, it is these that good architectural acoustics must be particularly careful to preserve and support in order to maintain intelligibility. In English, consonants carry much more information than vowels, as can readily be demonstrated by writing a sentence (1), then rewriting it without consonants (2), and then without vowels (3):

1. Most speech energy is concentrated in the one-hundred to six-hundred Hertz range.

2. o ee eey i oeae i e oe-ue o i-ue e ae.
3. Mst spch nrg s cncntrtd n th n-hndrd t sx-hndrd Hrtz rng.

The male voice centers its energy at around 500 Hz, the female voice at around 900 Hz. It is, however, in the high frequencies that consonants have most of their energy. Phonemes such as *s* and *sh*, for example, have most of their energy above 2 kHz, and both are particularly important in conveying intelligible content.

Normal speech averages between 55 and 65 dBA sound pressure level at 3 to 4 ft (0.9 to 1.2 m) from the source, with a dynamic range from about 30 dBA for soft speech to somewhat above 65 dBA for loud speech (at the same distance). Extremes of speech are 10 dBA for a soft whisper and 80 dBA for a shout, but in both of these instances intelligibility is sharply reduced because of lack of consonant power. In shouting, emphasis is actually on vowels, so that it is generally accepted that a 70-dBA sound pressure level is about the upper limit of fully intelligible human speech. Singers who frequently exceed 90 dBA do so at great loss of intelligibility.

Another result of the high-frequency content of consonants, and therefore intelligibility, is *directiveness*. The higher the frequency, the greater a sound's directivity, and the less its diffraction (ability to be heard beyond a partial barrier). Therefore, intelligibility of speech is greatest directly in front of a speaker and least behind him/her. High-frequency tones are most easily absorbed and least diffracted.

(b) Other Sounds

Instrumental music is much broader in dynamic range and more complex in frequency than speech. It has no direct parallel to intelligibility. A person's "reception" of music is a combination of physiological and psychological phenomena. As such, it is an experience beyond the scope of this book to cover in depth, but it is briefly examined in the subsequent discussion of room acoustics, auditoriums, and music halls. Noises are dealt with in Section 22.6.

22.5 EXPRESSING SOUND MAGNITUDE

Six different quantitative measures of sound magnitude are commonly encountered in architectural acoustics. Three of these—sound power, sound pressure, and sound intensity—are absolute measures; the other three—sound power level, sound pressure level, and sound intensity level—are ratio values that compare an absolute measure to a baseline reference value. Use of the qualitative metric of loudness is also common.

(a) Sound Power

Sound power is an independent property of a sound source that quantifies the source's acoustical output. Sound power is constant for any given source operating under defined conditions (a certain level of speech effort or a rotating speed on a motor) and is not influenced by the nature of the surroundings into which a source is placed. Thus, the sound power (output) of a chiller or orchestra is not changed by the distance to a receiver or the characteristics of a mechanical room or auditorium.

Sound power is expressed in watts (of acoustical power) and varies widely from source to source. Some selected sound power values are: a jet engine, 100,000 W; a symphony orchestra, 10 W; a loud radio, 0.1 W; normal speech, 0.000010 W. Note the wide range of values just in this sample: from 10^5 to 10^{-6} W. Sound power values for natural phenomena need to be obtained from an appropriate information source. Sound power data for manufactured equipment and devices can be obtained from the manufacturer. Manufacturers can often provide information on the sound power of a product under specified conditions. Manufacturers cannot provide accurate information on sound pressure levels, as these are influenced by environmental variables beyond the manufacturer's control or knowledge.

(b) Sound Pressure

Sound pressure is the deviation from ambient air pressure that is caused by sound waves. Sound pressure is instigated by the acoustic power output of a sound source, but is modified by the environment between the source and the receiver. Sound power is a characteristic of a source; sound pressure is the effect of a source as experienced at some specific location. Sound pressure must be referenced to a particular point in a space, because pressure will usually vary from location to location in a room.

Sound pressure is expressed in pascals (Pa) (or microbars in the I-P system). It is common practice to

TABLE 22.3 Comparison of Decimal, Exponential, and Logarithmic Statements of Various Acoustic Intensities

Intensity (W/cm^2)			
Decimal Notation	Exponential Notation	Intensity Level, Logarithmic Notation (dB)	Examples
0.001	10^{-3}	130	Painful
0.0001	10^{-4}	120	
0.00001	10^{-5}	110	75-piece orchestra
0.000001	10^{-6}	100	
0.0000001	10^{-7}	90	Shouting at 5 ft (1.5 m)
0.000000001	10^{-9}	70	Speech at 3 ft (0.9 m)
0.00000000001	10^{-11}	50	Average office
0.0000000000001	10^{-13}	30	Quiet, unoccupied office
0.00000000000001	10^{-14}	20	Rural ambient
0.000000000000001	10^{-15}	10	
0.0000000000000001	10^{-16}	0	Threshold of hearing

use SI units for all architectural acoustics metrics—even in the United States. Sound pressures for some common situations include: near a jet plane, 200 Pa; the threshold of pain, 20 Pa; a loud nightclub, 2 Pa; next to a highway, 0.2 Pa; and normal speech, 0.02 Pa. As with sound power, note the substantial range of values in these sample situations.

(c) Sound Intensity

The threshold of hearing—that is, the minimum sound intensity (I) that a normal ear can detect—is 10^{-16} W/cm^2. (The ear actually responds directly to pressure variations, but such pressures involve various energy densities.) The maximum sound intensity that the ear can accept without damage is approximately 10^{-3} W/cm^2. This gives an intensity range of 10^{13}, or 10 trillion to 1 (10,000,000,000,000:1). Table 22.3 gives an idea of the physical significance of these numbers. Note that the maximum (painful) acoustic intensity in Table 22.3 is 0.001 W/cm^2, or 10 W/m^2.

A point sound source of constant power radiating in free space—that is, at a location far from the effects of any reflecting surface—is represented in the drawing of Fig. 22.9. The *sound intensity* at any (defined) distance from the source is expressed as

$$I = \frac{P}{A} \tag{22.2}$$

where

I = sound (power) intensity, W/cm^2
P = acoustic power, W
A = area, cm^2*

since the sound radiates freely in all directions.

$$I = \frac{P}{4\pi r^2} \text{ W/cm}^2 \tag{22.3}$$

where r is the radius of an imaginary sphere enclosing the sound source. This is an implementation of the classic *inverse square law*, stating that *intensity is inversely proportional to the square of the distance from the source*. (In I-P units, this is

$$I = \frac{P}{930 \times 4\pi r^2} \text{ W/ft}^2 \tag{22.4}$$

since 1 ft^2 = 930 cm^2.) Using Equation 22.3 to determine the intensities I_1 and I_2 at distances r_1 and r_2 from point source P, we find that the intensities at distance r_1 and r_2 from the source stand in the ratio

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} \tag{22.5}$$

Figure 22.10 shows graphically how a sound pulse is attenuated in *strength* (but not in waveform) as it travels outward from a source by the action of distance.

The preceding derivation is based upon a *point* source—that is, a source that is small relative to the wavelength of the sound produced. This type of source produces spherical waves. Line sources, such

*It is traditional in architectural acoustics to express area in square centimeters, although the SI system requires area to be stated in square meters. Conversion data for units are given in Table 24.16. See also Table 24.17 for a listing of symbols and abbreviations.

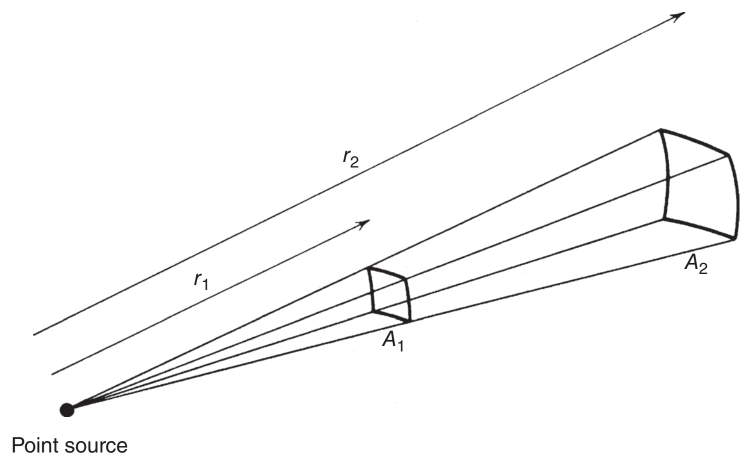


Fig. 22.9 *The same total energy passes through areas* A_1 *and* A_2. *Since* A *is proportional to the square of* r, *the energy density or intensity is inversely proportional to* r^2.

as strings, produce cylindrical waves. Large vibrating surfaces, such as walls, produce plane waves. The importance of these distinctions will become clear in the discussion of sound barriers and diffraction in Chapter 24.

(d) The Decibel

Two problems arise immediately when dealing with quantities of the type encountered with sound power, pressure, and intensity. The numbers themselves are very small or very large. Furthermore, the human ear responds logarithmically, not arithmetically, to sound pressure (or intensity); that is, doubling the intensity of a sound does not double its loudness—such a change is barely perceptible. To address these problems, it would be much more convenient if there were a scale that:

1. Started at zero for the minimum sound (intensity or pressure) that can be heard.
2. Used whole numbers rather than powers of 10.
3. Had some fixed relationships between an arithmetic difference and a loudness change, say, 10 units equals a doubling (or halving) of loudness. Thus, on such a scale, the difference between 20 and 30, between 60 and 70, would always be a doubling of loudness.

Such a scale exists. It is the decibel scale.

The word *level* when appended to power, pressure, or intensity indicates a quantity expressed relative to a base quantity—in decibels. *Intensity level* is thus the ratio between a given intensity and a base intensity. If intensity level is expressed as

$$IL = 10 \log \frac{I}{I_0} \tag{22.6}$$

where

IL = intensity level, dB
I = intensity, W/cm^2
I_0 = base intensity (i.e., 10^{-16} W/cm^2, the threshold of hearing)
log = logarithm to base 10

then a scale is established that satisfies the three conditions presented in this section. The quantity *IL* is dimensionless, since it indicates simply a ratio between two numbers. It is expressed in decibels, however, to clarify its status as a ratio

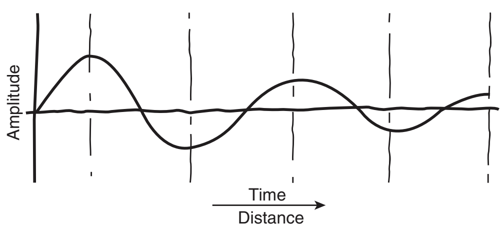


Fig. 22.10 *Attenuation of a sound signal in air as it travels away from the source. The shape (information) remains constant when traveling in a nondispersive medium such as air. This is not the case with travel in solids, where different frequencies travel at different velocities, causing a wave-shape change with time and distance. Since velocity of propagation is constant, time and distance are linearly related and can therefore be plotted on the same axis.(Drawing by Jonathan Meendering; © Walter Grondzik; all rights reserved.)*

quantity. This provides a convenient way to express the large range of sound magnitudes encountered. Table 22.3 shows the great convenience of using the logarithmic decibel scale, compared to either decimal notation or exponential notation. Table 22.2 gives a short listing of subjective loudness changes expressed in decibels. Note that *10 dB indicates a doubling of loudness*, and *20 dB a quadrupling of loudness*. The *difference* (Δ) between any two intensity levels can be expressed as

$$\Delta IL = IL_2 - IL_1 = 10\log\frac{I_2}{I_0} - 10\log\frac{I_1}{I_0}$$

Therefore,

$$\Delta IL = 10\log\frac{I_2}{I_1}\text{ dB} \tag{22.7}$$

A few examples using decibel notation and logarithmic calculations should help establish this useful system. By the way, the *bel* in decibel is in honor of Alexander Graham Bell (thus the capital *B* in dB).

EXAMPLE 22.1 Two sound sources (I_1 and I_2) produce intensity levels of 60 and 50 dB, respectively, at a point. When these sources are operating simultaneously, what is the total sound intensity level? (Assume identical frequency content and random phasing—that is, the phase relationship between the two sources changes in a random manner.)

SOLUTION

Note that this example deals with intensity level, not intensity, since intensity itself has little significance for architectural acoustics. The technique involved in adding two sound intensity levels has three steps:

1. Convert both to actual intensity.

$$IL = 10\log\frac{I}{I_0}$$

so

$$60 = 10\log\frac{I_1}{10^{-16}}$$

or

$$6.0 = \log\frac{I_1}{10^{-16}}$$

Then, using the definition of a base 10 logarithm:

$$10^6 = \frac{I_1}{10^{-16}}$$

$$I_1 = (10^{-16})(10^6) = 10^{-10}\text{ W/cm}^2$$

By similar calculation,

$$I_2 = 10^{-11}\text{ W/cm}^2$$

2. Add the intensities arithmetically.

$$\begin{aligned} I_1 + I_2 &= 10^{-10} + 10^{-11} \\ &= (10\times10^{-11}) + 10^{-11} \\ I_{tot} &= 11\times10^{-11}\text{ W/cm}^2 \end{aligned}$$

3. Reconvert to decibels. To find the intensity level (IL) corresponding to the combined or total intensity $I_1 + I_2$, simply apply Equation 22.6:

$$\begin{aligned} IL_{tot} &= 10\log\frac{I_{tot}}{I_0} \\ &= 10\log\frac{11\times10^{-11}}{10^{-16}} \\ &= 10(\log 11 + \log 10^5) \\ &= 10(1.04 + 5) \\ &= 60.4\text{ dB} \end{aligned}$$

which is only a fraction larger than the original 60 dB of the stronger of the two sounds. As demonstrated in this example, decibels cannot be added arithmetically. ■

EXAMPLE 22.2 Assume two sounds of 60 dB each. What is the combined sound intensity level in decibels?

SOLUTION

One method would be to calculate levels as in Example 22.1. A shorter method is to find the difference between the sum and either of the (equal) signals and add it to either individual signal. Using Equation 22.7:

$$\begin{aligned} \Delta IL = IL_{comb} - IL_1 &= 10\log\frac{I_{comb}}{I_1} \\ &= 10\log\frac{2I_1}{I_1} \\ &= 10\log 2 \\ &= 10(0.30) \\ &= 3\text{ dB} \end{aligned}$$

This answer (which is independent of any particular sound level) yields the extremely important and useful fact that *doubling a signal's intensity raises the intensity level by 3 dB*. (In this case, the combined intensity level would be 60 dB + 3 dB, or 63 dB.) Similarly, quadrupling a signal's intensity raises the resulting level by 6 dB. This is because

$$\begin{aligned}\Delta IL &= 10 \log \frac{4I}{I} \\ &= 10 \log 4 \\ &= 10\,(0.60) \\ &= 6 \text{ dB}\end{aligned}$$

Therefore, quadrupling 60 dB gives 66 dB (or, alternatively, 60 dB + 60 dB = 63 dB and 63 dB + 63 dB = 66 dB). This technique is very useful when combining a large number of identical sound levels, as in the following example. ■

EXAMPLE 22.3 A factory will contain 20 identical machines, each of which generates a sound intensity level of 80 dB. What will be the combined sound intensity level? (Ignore issues of frequency content, phase, and sound fields.)

SOLUTION

$$\begin{aligned}\Delta IL &= IL_{\text{tot}} - IL_{\text{single}} \\ &= 10 \log \frac{I_{\text{tot}}}{I_{\text{single}}} \\ &= 10 \log \frac{20\, I_{\text{single}}}{I_{\text{single}}} \\ &= 10 \log 20 \\ &= 10\,(1.3) = 13 \text{ dB}\end{aligned}$$

Therefore, the total sound intensity level will be $IL_{\text{tot}} = 80 \text{ dB} + 13 \text{ dB} = 93 \text{ dB}$ ■

A chart for combining the decibel levels of two sources, given in Fig. 22.11, eliminates the somewhat lengthy procedure detailed in Example 22.1. Referring to Table 22.2, note that the human ear is not responsive to fractional decibel changes; indeed, even a 3-dB change is barely perceptible. This being so, it is recommended that the detailed calculations, and even the chart, be reserved for situations where a high degree of accuracy is required.

For everyday calculations, the following approximations may be used to combine the decibel levels of two sources:

- When the difference between two sources is 1 dB or less, add 3 dB to the higher decibel level to obtain the total.
- When the difference is 2 to 3 dB, add 2 dB.
- When the difference is 4 to 8 dB, add 1 dB.
- When the difference is 9 dB or more, ignore the lower-level source (add 0 to the higher).

A comparison in Table 22.4 of addition using these rules and a more accurate method shows

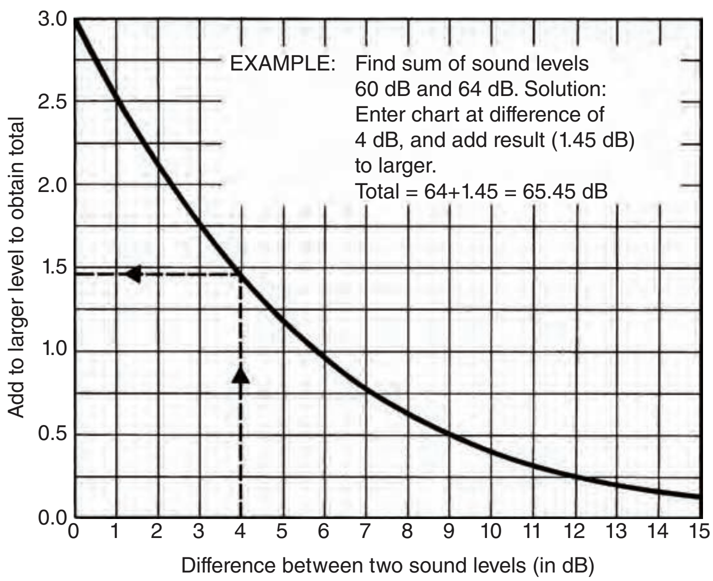


Fig. 22.11 Chart for adding two uncorrelated sound pressure levels when both are expressed in decibels. (Reprinted by permission from E. B. Magrab. 1975. Environmental Noise Control. *John Wiley & Sons, Hoboken, NJ.)*

TABLE 22.4 Addition of Uncorrelated Sound Pressure Levels

dB Levels		Sum	
Lower	Higher	Approximate[a]	Accurate[b]
60	60	63	63.0
60	62	64	64.4
60	64	65	65.5
60	66	67	67.0
60	68	69	68.7
60	70	70	70.5

[a]See text for approximation rules.

[b]In architectural acoustics, decimal values of decibels are not warranted, and these values would be rounded off to a whole number

that, at usual levels, the error resulting from simplification is always less than 1%.

Returning to the inverse square law expressed in Equation 22.5, it is now possible to determine the effect on sound intensity level of moving away from a sound source.

EXAMPLE 22.4 Given a sound source that produces an intensity level *IL* at a distance d_1 from a source (substitute any numbers desired or follow the problem with symbols), what is the intensity level at twice the distance? At four times the distance?

Note: A sound intensity distribution that obeys the inverse square law on which these calculations are based results from a source in an open (unenclosed), obstruction-free space (e.g., outdoors). Also, intensity measurement I_1 must be taken at a sufficient distance d_1 from the source that a free field has developed. See the discussion in Section 23.7 for an explanation of sound fields.

SOLUTION

From Equation 22.7 it is known that

$$\Delta IL = \frac{I_2}{I_1}$$

and from Equation 22.5 that

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}$$

Therefore, since $d_2 = 2d_1$

$$\frac{I_2}{I_1} = \frac{(d_1)^2}{(2d_1)^2} = \frac{1}{4}$$

Substituting in Equation 22.7, we have

$$\begin{aligned}\Delta IL &= 10 \log \frac{I_2}{I_1} \\ &= 10 \log \tfrac{1}{4} \\ &= 10\,(-0.6) \\ &= -6 \text{ dB}\end{aligned}$$

which tells us that sound intensity level (not pressure) is reduced by 6 dB. Similarly, if the distance is quadrupled, it is reduced by 12 dB. ■

To summarize, *the intensity level changes by 3 dB with every doubling or halving of power and changes by 6 dB with every doubling or halving of the distance from a point source*. Figures 22.12 and 22.13 illustrate the latter relationship.

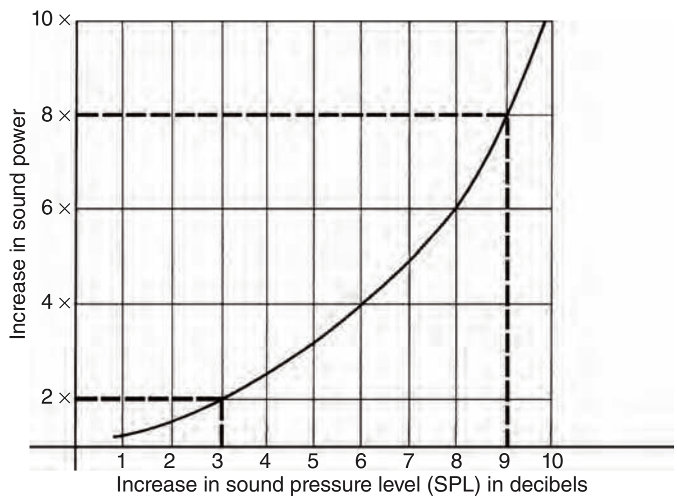


Fig. 22.12 *Decibel level increase as a function of power (intensity) increase.*

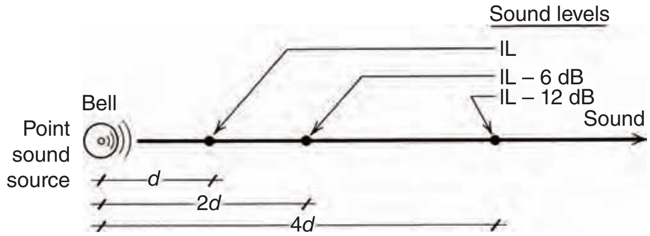


Fig. 22.13 *Sound energy levels at varying distances from a source. Each doubling of distance reduces the intensity level by 6 dB. These relationships hold true only in a free field.*

(e) Sound Power Level

Sound power levels may be derived from sound power values using the ratio process described in Section 22.5(d). The reference sound power is 10^{-12} W. Sound power level is expressed in decibels.

(f) Sound Pressure Level

Sound pressure levels are derived from sound pressures using the ratio approach described in Section 22.5(d). The usual reference sound pressure corresponds to the threshold of hearing and is taken to be 20 μPa or 2×10^{-5} Pa (2×10^{-4} microbars [μbar]). See Table 22.5 for representative values of sound pressure levels and corresponding subjective responses. As with intensity, this sound pressure reference is established as 0 dB for the purpose of calculating sound pressure *level*. Since the ear responds logarithmically to intensity and since pressure varies as the square root of intensity, we can write the expression

$$SPL = 10 \log \frac{p^2}{p_0^2}$$

or

$$SPL = 20 \log \frac{p}{p_0}$$

where
SPL = sound pressure level, dB
p = pressure, Pa or μbar
p_0 = reference base pressure, 20 μPa or 2×10^{-4} μbar

Since the 0-dB base corresponds to the hearing threshold for both sound intensity level and sound pressure level, the decibel scales for sound pressure level and sound intensity level have been equalized *and the decibel values of the two can be used interchangeably*. The actual intensity and the actual pressure corresponding to a particular decibel level, however, are different—completely different—in magnitude and units. For instance, 70 dB may equal 10^{-9} W/cm^2 intensity or 0.063 Pa pressure. The important fact, though, is that 70 dB corresponds approximately to a particular sound magnitude. It is necessary to say "approximately" because assigning a single-number decibel level to a sound presents two difficulties:

1. Sound pressure level varies with time, except for a pure steady tone.
2. The different components of most common (complex) sounds vary in pressure level.

Two techniques are used to overcome this problem. If a sound has a dominant frequency, that frequency's level can be used (Fig. 22.8). This would be the case for a relatively constant sound such as that of a motor, fan, or pump. Other sounds that vary widely in constituent level and frequency can be plotted on an octave band chart using maximum level for minimum percentage of time (Fig. 22.14). Where the position of the listener is not specified in the table, it is assumed to be at normal *close* distances: that is, 10 to 20 ft (3 to 6 m) from a train, 3 to 5 ft (0.9 to 1.5 m) from a radio, and the like.

As suggested previously, the combined effect of two sounds depends upon their frequency content. In the foregoing examples, we assumed signals either of identical frequency and random phase or of a very-wide-frequency spectrum—so wide that phase phenomena are not significant. In architectural acoustics work, such an assumption is generally valid.

TABLE 22.5 Common Sound Pressure Levels

Sound Pressure Level (dBA)	Typical Sound	Subjective Impression
150		(Short exposure can cause hearing loss)
140	Jet plane takeoff	
130	Artillery fire, riveting, machine gun	(Threshold of pain)
120	Siren at 100 ft (30 m), jet plane (passenger ramp), thunder, sonic boom	Deafening
110	Woodworking shop, hard-rock band, accelerating motorcycle	Sound can be felt (threshold of discomfort)
100	Subway (steel wheels), loud street noise, power lawnmower, outboard motor	
90	Noisy factory, unmuffled truck, train whistle, machine shop, kitchen blender, pneumatic jackhammer	Very loud, conversation difficult; ear protection required for sustained occupancy
80	Printing press, subway (rubber wheels), noisy office, supermarket, average factory	(Intolerable for phone use)
70	Average street noise, quiet typewriter, freight train at 100 ft (30 m), average radio, department store	Loud, noisy; voice must be raised to be understood
60	Noisy home, hotel lobby, average office, restaurant, normal conversation	
50	General office, hospital, quiet radio, average home, bank, quiet street	Usual background; normal conversation easily understood
40	Private office, quiet home	
30	Quiet conversation, broadcast studio	Noticeably quiet
20	Empty auditorium, whisper	
10	Rustling leaves, soundproof room, human breathing	Very quiet
0		Intolerably quiet Threshold of audibility

(g) Measuring Sound

The need for a means of measuring sound levels in built projects to confirm that design criteria have been met should be obvious. One very useful instrument is the integrating sound-level meter illustrated in Fig. 22.15. To correlate meter readings with subjective loudness impressions, most such instruments that provide a single-number output are furnished with weighting networks, the characteristics of which are given in Fig. 22.16. The A network corresponds to an inverted 40-phon contour and discriminates against low frequencies (see Fig. 22.7), as does the human ear. The B and C networks correspond to the 70-phon and 100-phon

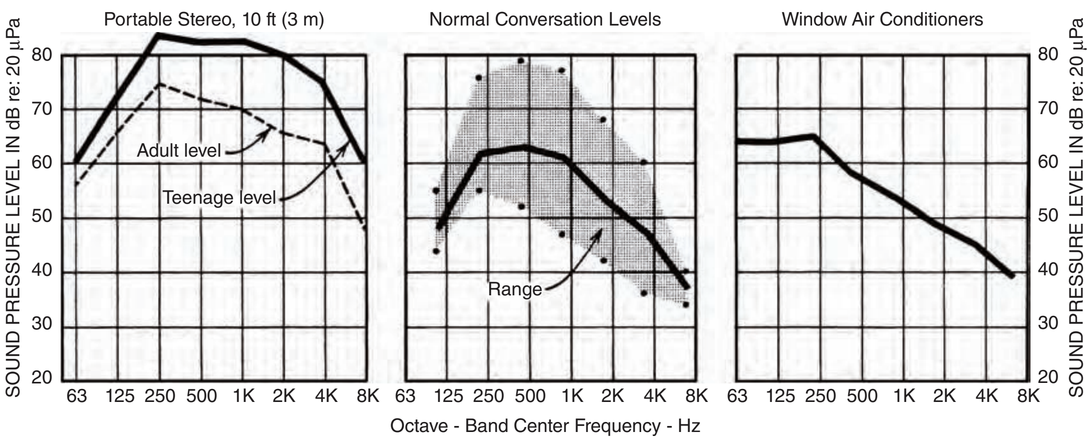


Fig. 22.14 *Sound pressure level curves of common noise sources plotted according to octave band frequency content. Values shown are averages of multiple measurements. Reprinted from HUD,* A Guide to Airborne, Impact, and Structure Borne Noise-Control in Multifamily Dwellings, *1968.*

Fig. 22.15 General-purpose (type 2) integrating, data-logging sound level meter. This handheld unit will measure and record isolated, nonrepetitive sounds in addition to continuous, fluctuating, and impulsive sounds, and will give both instantaneous and equivalent (Leq) sound levels. The latter are used when an equivalent noise level of varying sound conditions over a selected measurement time is required. The meter will measure dBA, dBC, and linear with fast, slow, peak, or impulse response. When equipped with a filter set, the meter can be used for octave or 1/3-octave analysis. (© 2013 3M. All rights reserved.)

contours, respectively. In addition, a completely linear response is usually available. The reasoning behind the use of these weighting networks is evident when they are compared to the equal loudness curves of Fig. 22.7. The original intention was to use the A network at levels of up to 55 phons, the B network to 85 phons, and the C network at higher levels. In practice, however, it was found that only the A network corresponded fairly well to subjective loudness reports. As a result, the B network has fallen into disuse, and the A network is used today for all measurements, regardless of loudness. The discrepancy at high loudness levels is apparent when the 40-phon A weighting network curve is compared to the equal loudness curves above 80 phon. All measurements should be identified with the weighting network used, such as 50 dBA or 100 dBC.

More accurate measurements of complex sounds than are possible with a standard sound level meter are made with sophisticated instruments that measure intensity in octave bands and also often plot the results, as per the graphs in Fig. 22.14. Such measurements are necessary for accurate application of sound absorption and attenuation materials whose characteristics are nonlinear over the frequency spectrum.

Single-number dBA readings are known as *overall* levels and are useful as preliminary data and for broad-spectrum design. Table 22.5 lists common sound levels as measured by the dBA scale. Such single-value numbers are useful to establish a mental-aural comparison base and for use in maximum noise exposure calculations, as discussed in the following section.

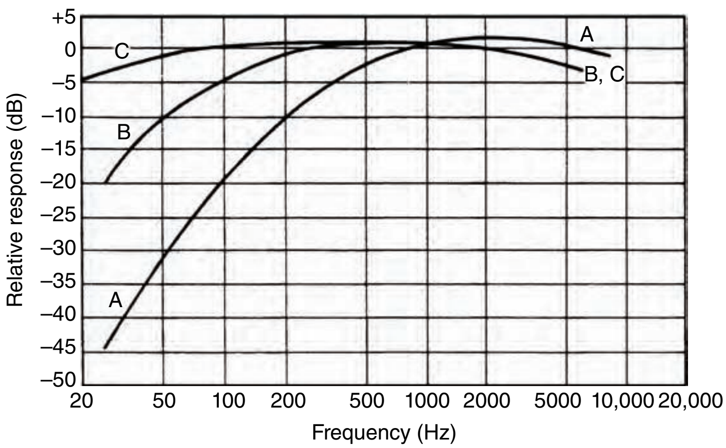


Fig. 22.16 Internationally standardized A, B, and C weighting curves.

22.6 NOISE

Noise is variously defined as unwanted sound, sound with no intelligible content, and/or broadband sound, depending upon the listener and the situation. Each definition is appropriate for various times and situations. It should generally be assumed that any sound can at some point be referred to as noise by someone.

Although noise effects and their control are the specific subject of Chapter 24, noise criteria and their development are discussed here as part of an overall view of hearing and sound sources. There are two basic approaches to the negative effects of noise: a psychological-practical one, and a purely physiological one. The latter is concerned with the physical impact of noise on the body, including hearing loss and other deleterious conditions. The former is concerned with noise levels that cause annoyance and disturbance to daily activities, including work, relaxation, and rest.

(a) Annoyance

Research has developed accurate data on perceptions of loudness. The concept of annoyance, however, being primarily subjective and psychological, is much more elusive. Tests have shown that *in general*, annoyance as a result of noise is:

1. Proportional to the loudness of the noise
2. Greater for high-frequency than low-frequency noise
3. Greater for intermittent than continuous noise
4. Greater for pure-tone than for broadband noise
5. Greater for moving or unlocatable (reverberant) noise than for fixed-location noise
6. Much greater for information-bearing noise than for nonsense noise

(b) Noise Criteria

To establish criteria for *acceptable background noise* (i.e., noise whose extent of annoyance is considered acceptable), certain of these effects must be neglected at this point for the sake of simplicity. They can be and are considered in design and in establishing levels of masking noise (see Chapter 24.) Thus, ignore, for the time being, these factors from the list in the preceding section:

Factor 3, assuming, instead, continuous sounds

Factor 4, as broadband noise is assumed

Factor 5, as the noise source is assumed to be fixed in location

Factor 6, assuming that we can only consider general noise level, not actual content

Thus, the particular and special characteristics of noises such as a barking dog (3), a whistle (4), a single passing vehicle (5), and intelligible sounds (6) are not considered when establishing conventional noise criteria.

In order to quantify the concept of acceptable background noise, it was necessary to remove it from the purely psychological arena and relate it to a physical phenomenon. This was done by studying the effect of the two remaining annoyance factors (1 and 2) on speech communication. This study resulted in two design concepts: the Articulation Index (AI) and the Speech Interference Level (SIL). These are both determined by reading a carefully selected set of phonetically balanced nonsense syllables to a test audience in the presence of different levels and compositions of background noise. The ratio of correctly identified syllables to total syllables read is the Articulation Index. An AI in excess of 0.5 was considered indicative (Beranek, 1988a) of a condition in which acceptable intelligibility could be expected for *male* voices. The Speech Interference Level, a simplified version of the AI, was devised by Beranek. It consists simply of the arithmetic average in decibels of the background sound pressure levels in the four octave bands centered on 500, 1000, 2000, and 4000 Hz, for which acceptable intelligibility could be expected, for a given voice effort, at a given distance between the speaker and listener.

(c) Noise Criteria Curves

Beranek also developed the well-known and widely accepted and used noise criteria (NC) curves shown in Fig. 22.17. The NC curves are based on the consideration that most people prefer to speak at a level no greater than 22 dB above the background noise level. The NC curves are derived by combining the SILs in decibels with this behavioral phenomenon; they represent a loudness level 22 dB higher than

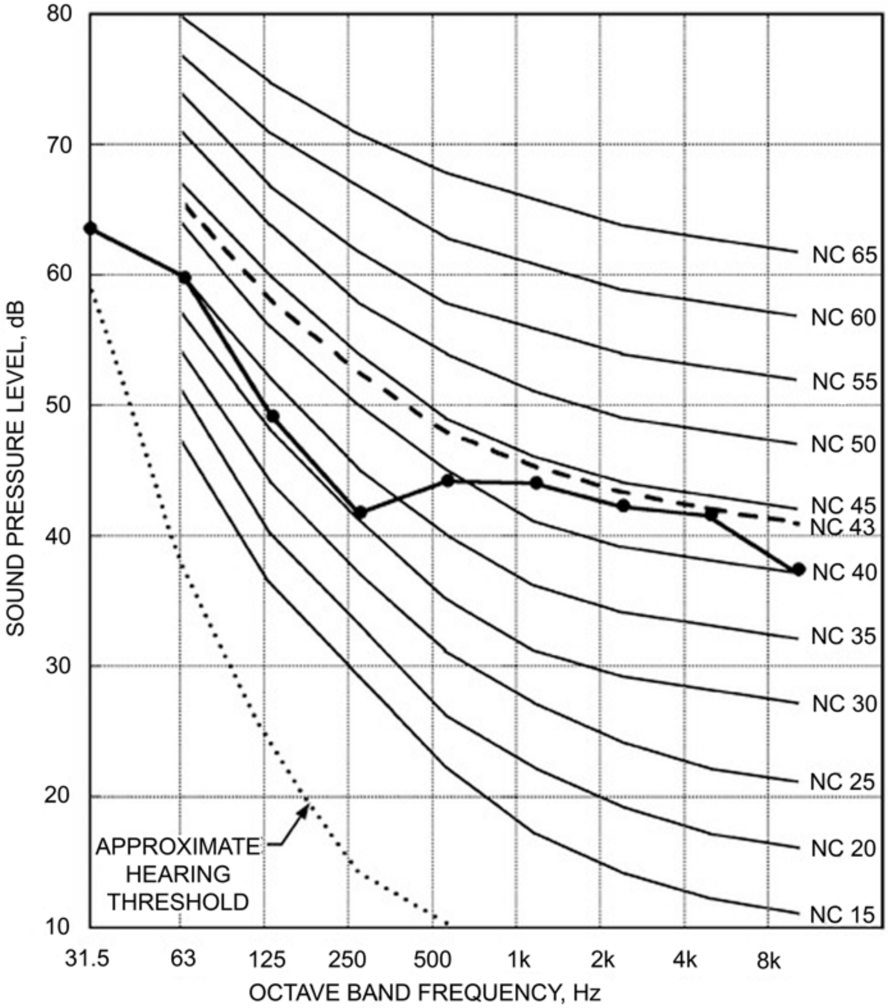


Fig. 22.17 *Application of NC curves. The typical spectrum plotted would be rated NC-36, as it exceeds NC-35 at 500 Hz by 1 dB. See Table 24.7 for specific NC recommendations for interior spaces. (Reprinted with permission; ©ASHRAE 2011* ASHRAE Handbook—HVAC Applications.*)*

the SIL. The contours then represent the maximum *continuous* background noise likely to be considered acceptable in a specified environment, and generally correspond to background sound pressure (noise) levels found reasonably acceptable in selected commercial/institutional building environments. A similar set of curves called *noise rating* (NR) curves find considerable application outside the United States. They are less stringent than NC curves in low frequencies but more stringent in high frequencies.

To apply the NC curves, the spectrum (from 63 to 8000 Hz) of a specific noise being studied is overlaid on a graph of the NC curves. The lowest NC curve that is not exceeded by any portion of the plot becomes the NC rating of the particular noise. Thus, specifying a maximum noise level of NC-30 for a space means that no portion of the sound pressure level curve of any continuous background noise in the space may cross the NC-30 contour. A piece of equipment rated NC-35 has an octave-band spectrum completely below NC-35. A fan rated NC-53 indicates that at some point in its frequency spectrum the fan exceeded NC-50 by 3 dB.

The NC rating of a noise usually falls between 5 and 10 dB below the measured dBA for the noise, depending upon the shape of the noise spectrum.

The virtue of the NC curves is that they provide a single-number specification for sound across a wide frequency range—without losing all sense of the frequency distribution. Their disadvantage is that they were derived for, and are most accurate with, speech conversation conducted against a backdrop of continuous, broadband noise. This is not the situation that is typically most troublesome in an office; indeed, continuous equipment noise may be *helpful* in masking unwanted speech. Nevertheless, NC curves remain the most commonly used criteria for establishing acceptable continuous background noise levels.

(d) Room Criteria Curves

Due to the recognized shortcomings of the criteria inherent in the NC curves—specifically that they are undefined in the very low frequencies (16 and 31.5 octave bands) and are not sufficiently stringent at frequencies above 2 kHz—a similar approach to setting criteria was developed, called *room criteria* (RC) curves. These curves, shown in Fig. 22.18, were adopted by ASHRAE (the American Society of Heating, Refrigerating and Air-Conditioning Engineers) as the suggested noise limitation benchmark, in

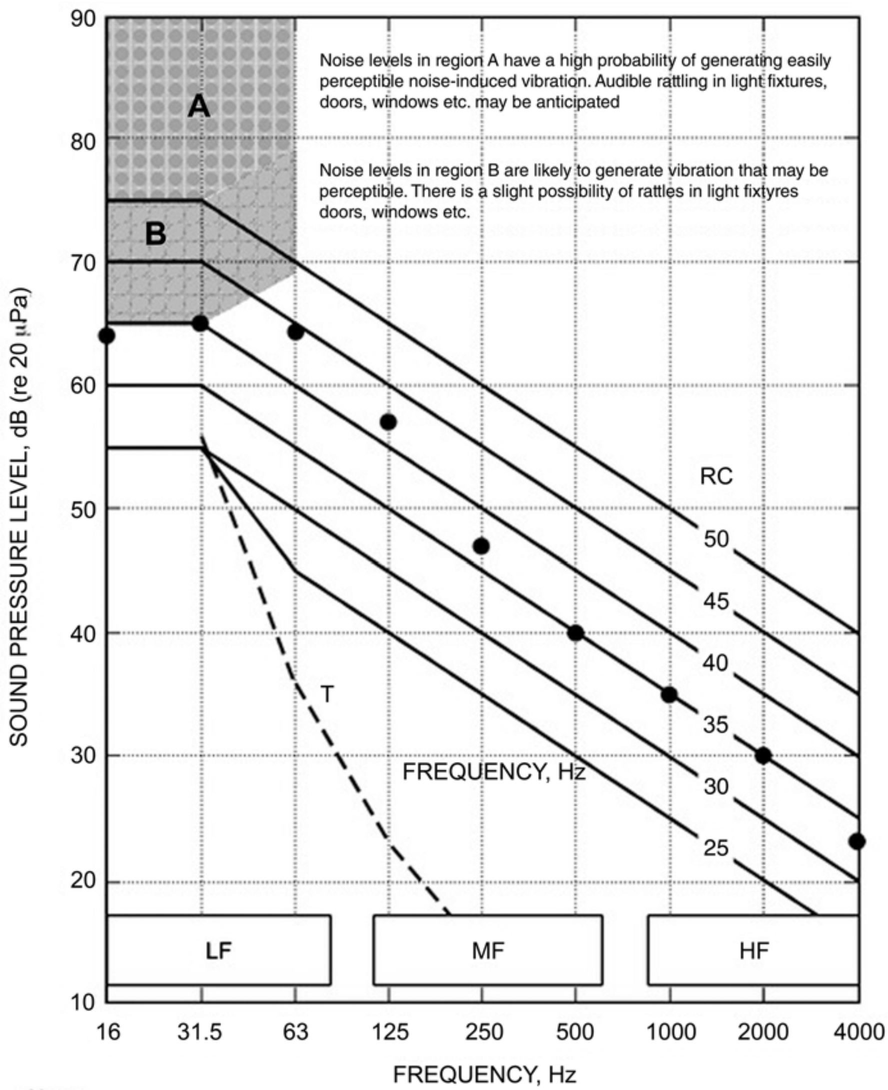


Fig. 22.18 *RC curves. These curves were adopted by ASHRAE in lieu of NC curve criteria. See text for an explanation of their use. Reprinted with permission; © ASHRAE 2011* ASHRAE Handbook—HVAC Applications.

preference to NC curves. The curves are intended to evaluate the acceptability of background mechanical system noise for typical space types. RC curves differ from NC curves in a number of aspects:

- They are straight lines.
- Their slope is constant at −5 dB per octave (determined from extensive tests, mostly in the range of 40–50 dB).
- Regions labeled A and B, as in Fig. 22.18, address the problem of very low frequencies and high sound pressure levels, an issue that is ignored in the NC criteria. These regions deal with rumble and vibration that can cause extreme annoyance for many occupants.

Referring to Fig. 22.18, the procedure for determining the RC value of a specific item of equipment whose noise spectrum is known is as follows:

1. Calculate the arithmetic average of the sound pressure levels (SPL) in the 500-, 1000-, and 2000-Hz octave bands. This number is the RC value of that noise spectrum.
2. Draw a straight line at a −5 dB slope through this value of RC at 1000 Hz.
3. Plot the SPL values for the octave band center frequencies on the RC curve sheet and compare the plot to the RC line drawn in step 2.
4. Classify the equipment sound quality from this comparison as follows:
   a. *Neutral.* If the octave band data plotted in step 3 do not exceed the RC line drawn in step 2 by more than 5 dB at or below 500 Hz and more than 3 dB at or above 1000 Hz, then the sound is considered neutral (bland, uncharacteristic), and the designator letter *N* is placed after the RC level. A piece of mechanical equipment with an *N* designation is then understood to have a neutral tone quality that most people would classify as unobtrusive and lacking specific character. ASHRAE design guidelines for HVAC system noise levels are listed as RC (*N*).
   b. *Rumble.* If the octave band plot *does* exceed the RC line by more than 5 dB at 500 Hz or below, the spectrum is classified as "rumbly," and the descriptor letter *R* is appended to its RC level number.
   c. *Hiss.* If the octave band plot *does* exceed the RC line by more than 3 dB at or above 1000 Hz, it is classified as "hissy," and the descriptor letter *H* is appended to its RC level.
   d. *Vibration.* The shaded areas in Fig. 22.18 labeled A and B represent high sound pressure levels in the 31.5- and 63-Hz octave bands. In the A area, vibration will likely be felt in light construction and furniture, and rattling may occur in loosely constructed devices, cabinets, glassware, and the like. In the lower-energy B area, rattling will be less likely but vibration may still be felt.

The result of this classification is to give the designer not only an average SPL for an item of equipment, but also a sense of subjective sound quality that should be of considerable assistance in determining the noise abatement measures to be taken.

ASHRAE has updated the RC curve concept to what is now called the *RC Mark II* method. This updated method is a bit more complex than the original RC approach. For further information, see the *ASHRAE Handbook—HVAC Applications* (ASHRAE, 2011). The original NC curves have also been modified (by Beranek) and issued as balanced noise criteria (NCB) curves. They amended a failing of the NC approach by adding very-low-frequency coverage, and the NCB curves were straightened, so that they resemble RC curves above 125 Hz, except that the slope angle is −3.33 dB, compared to −5 dB for the RC curves. The slope at the higher frequencies has also eliminated the hiss that characterizes equipment noise conforming to the NC criteria. These adjustments have yielded a "balanced" neutral sound, which reflects the chart's name. Application of these curves to mechanical equipment noise is similar to that for RC curves, except that letter descriptors are not used. For a full discussion of the construction and application of BNC curves, see Beranek (1988b). Given these competing options for criteria, selection of NC, RC, RC Mark II, or NCB criteria for background noise is a function of design intent. The approach that best meets the needs (and budget) of the owner should be chosen.

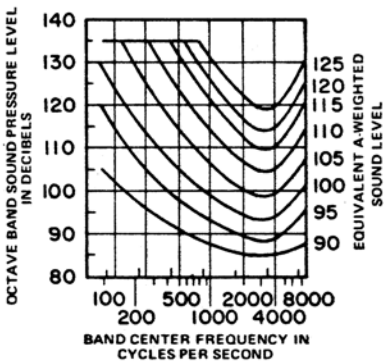
(e) High Noise Levels and Hearing Protection

It has long been recognized that continuous exposure to high noise levels causes a degree of temporary deafness in most people and that long periods of such exposure, even on an intermittent 8-hour workday basis, can produce permanent hearing impairment. Most experts place the safe 8-hour upper limit at 85 dBA. In addition, studies have indicated that continual exposure to noise levels as low as 75 to 85 dBA can produce or contribute to numerous physical and psychological ailments, including headache, digestive problems, tachycardia, high blood pressure, anxiety, and nervousness—an extensive catalog of human illnesses. Since continuous noise exposure is most severe in industry, regulatory legislation in the United States has been directed at this area.

In 1969 the Walsh-Healey Public Contracts Act was passed, and thereafter its provision for maximum permissible exposure to noise levels was incorporated into the Occupational Safety and Health Act. Both the act and the associated regulatory agency, the Occupational Safety and Health Administration, are known as OSHA. The relevant provisions of this act are reproduced in Fig. 22.19.

§ 1910.95 Occupational noise exposure.

(a) Protection against the effects of noise exposure shall be provided when the sound levels exceed those shown in Table G-16 when measured on the A scale of a standard sound level meter at slow response. When noise levels are determined by octave band analysis, the equivalent A-weighted sound level may be determined as follows:



Equivalent sound level contours. Octave band sound pressure levels may be converted to the equivalent A-weighted sound level by plotting them on this graph and noting the A-weighted sound level corresponding to the point of highest penetration into the sound level contours. This equivalent A-weighted sound level, which may differ from the actual A-weighted sound level of the noise, is used to determine exposure limits from Table G-16.

[1910.95 amended at 39 FR 19468, June 3, 1974]

(b)(1) When employees are subjected to sound exceeding those listed in Table G-16, feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of Table G-16, personal protective equipment shall be provided and used to reduce sound levels within the levels of the table.

(2) If the variations in noise level involve maxima at intervals of 1 second or less, it is to be considered continuous.

(3) In all cases where the sound levels exceed the values shown herein, a continuing, effective hearing conservation program shall be administered.

TABLE G-16—PERMISSIBLE NOISE EXPOSURES[1]

Duration per day, hours	Sound level dBA slow response
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
¼ or less	115

[1] When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions: $C_1/T_1 + C_2/T_2 + \cdots C_n/T_n$ exceeds unity, then, the mixed exposure should be considered to exceed the limit value. Cn indicates the total time of exposure at a specified noise level, and Tn indicates the total time of exposure permitted at that level.

[1910.95 Table G-16 amended at 39 FR 19468, June 3, 1974]

Exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level.

Fig. 22.19 *The standard for exposure to noise in the workplace. (From OSHA, July 1988; current as of late 2013.)*

Fig. 22.20 *A noise dosimeter. The unit is carried by a person whose noise exposure is being tested, with the clip-mounted microphone at shoulder (ear) level. The meter will display, store, and calculate maximum, minimum, and peak levels of SPL, Leq, TWA, exposure levels, and dosage. Noise-level histories are stored and can be printed out as desired. The unit shown measures 5.5 × 2.8 × 1.4 in. (140 × 70 × 40 mm) and weighs 15.5 oz (440 g). (Photo courtesy of Quest Technologies.)*

To avoid overly complex regulations, limitations on exposure are given as single-number dBA values. Since workers rarely remain in a single acoustic environment for 8 hours, their total daily exposure, or *time-weighted average* (TWA) exposure, can be calculated from timed dBA measurements, using formulas and tables given by OSHA, and then compared to permissible levels. Alternatively, a dosimeter (Fig. 22.20) can be used, which automatically integrates the noise to which a person is exposed over a given time period and reads out the permissible TWA exposure directly.

Typical industrial noise levels are given in Table 22.6. When permissible levels are exceeded, management must take steps to reduce the exposure, either by reducing the noise or by providing hearing protectors. Typical characteristics of a few types of ear protectors are given in Fig. 22.21. Photographs of three of the most common types of ear protectors in industrial use are shown in Fig. 22.22.

OSHA does not deal extensively with impulse noises, except to state that they shall not exceed a 140-dB peak sound pressure level. Impulse noise is quite different from continuous noise, since effective noise levels depend on duration, and specification is difficult. Much work has been done in this area by the military, for obvious reasons. The interested reader is referred to the literature, since this subject is substantially outside the realm of architectural acoustics.

TABLE 22.6 Typical Industrial Noise Levels[a]

Equipment	dBA
Printing press plant (medium-sized automatic)	86
Heavy diesel-propelled vehicle (about 25 ft [7 m] away)	92
Heavy-duty grinder	93
Air compressor	94
Plastic chipper	96
Cutoff saw	97
Multiple spot welder	98
Turbine condenser	98
15-cu-ft (425-L) air compressor	100
Drive gear	103
Banging of steel plate	104
Magnetic drill press	106
Air chisel	106
Positive displacement blower	107
Air hammer	107
Vacuum pump	108
Jolt squeeze hammer	122

[a]These are approximate values for some typical generic equipment types and should not be used as design values.

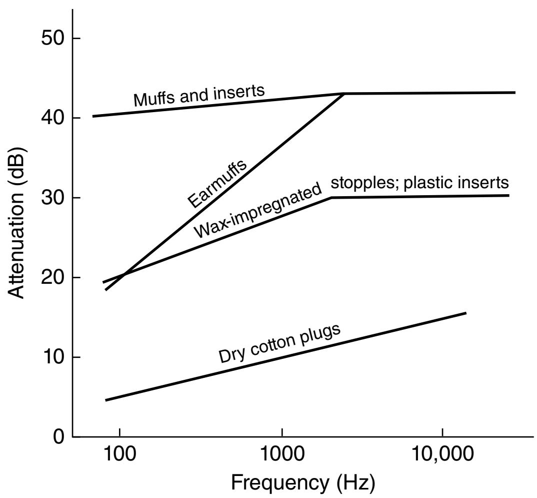


Fig. 22.21 *Sound attenuation characteristics typical of various types of ear protectors. For design purposes, specific attenuation characteristics must be used and the attenuation figures modified to reflect field usage. (From* Quieting: A Practical Guide to Noise Control, *NBS. 1976.)*

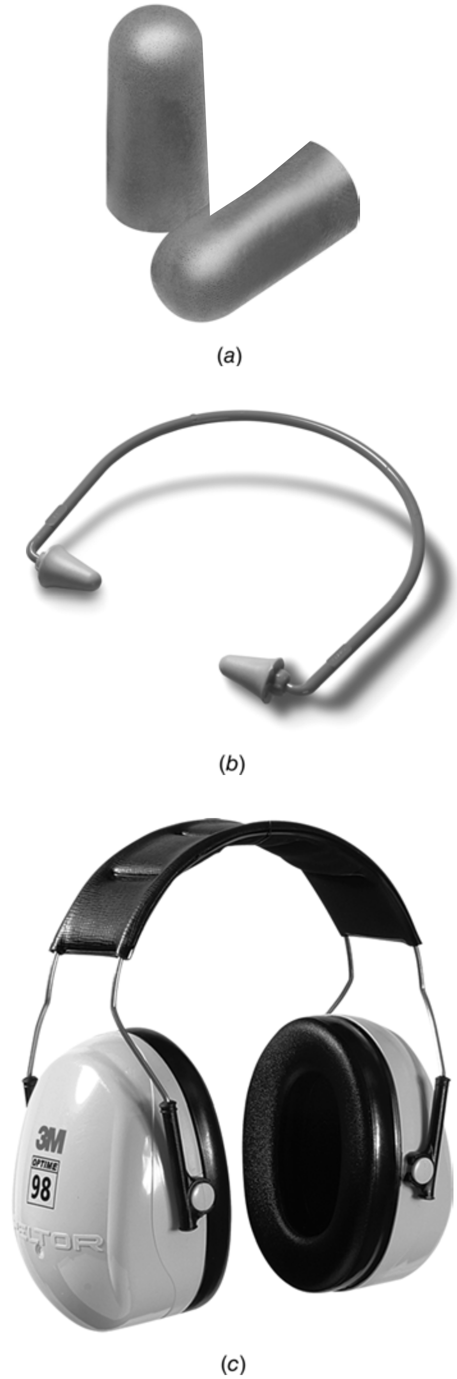


Fig. 22.22 *Three common types of ear protection devices: (a) PVC foam ear plugs are rolled and squeezed to reduce their diameter before being placed in the ear canal, where they re-expand to their previous size. After a single use, they are generally discarded. The ear plugs have an EPA noise reduction rating (NRR) of 32 when tested to ANSI 53.19-1974. In 1997, ANSI updated the standard to S12.6-1997 for testing to take place under "real-world" conditions instead of laboratory conditions. However, manufacturers still continue to utilize ANSI 53.19-1974; therefore the National Institute for Occupational Safety and Health (NIOSH) recommends multiplying by a percent efficacy. (b) Ear protector for intermittent use consists of (replaceable) foam pads mounted on a flexible neck band. The foam does not require rolling. The unit is rated NRR 28. (c) Spring-type headband and foam-filled ear cushions provide an NRR rating of 30 for this earmuff design. (© 2013 3M. All rights reserved.)*

22.7 VIBRATION

Sound is heard; vibration is felt. If sound is defined as a pressure variation that is audibly received, then vibration is a tactilely received pressure variation. Vibrations of concern to building design have frequencies that begin just below the range of human hearing at around 20 Hz. For someone with a hearing threshold above 20 Hz, the vibration sensation frequency might be higher. The means of reception of the energy is more important than specific frequency cutoffs. In general, vibration in a building is always an unwanted experience. Most mechanical and electrical equipment produces energy output that will be sensed as noise and output that will be sensed as vibration. Various means of vibration control are presented in Section 22.26. As vibration is not received through the sense of hearing, vibration mitigation approaches are quite different from noise mitigation approaches.

References and Resources

ASHRAE. 2011. *ASHRAE Handbook—HVAC Applications*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, GA.

Beranek, L. L. 1988a. *Acoustical Measurements*, revised ed. Acoustical Society of America. Melville, NY.

Beranek, L. L. 1988b. *Noise and Vibration Control*, revised ed. Institute of Noise Control Engineering. Washington, DC.

Classroom acoustics. http://www.quietclassrooms.org/

HUD. 1968. *A Guide to Airborne, Impact, and Structure Borne Noise–Control in Multifamily Dwellings*. U.S. Department of Housing and Urban Development. Washington, DC.

Magrab, E. B. 1975. *Environmental Noise Control.* John Wiley & Sons. New York.

NBS. 1976. *Quieting: A Practical Guide to Noise Control* (Handbook 119). National Bureau of Standards (now NIST). Washington, DC.

Noise Pollution Clearinghouse: http://www.nonoise.org/

U.S. Department of Labor, Occupational Safety & Health Administration (OSHA). "Occupational Noise Exposure." http://www.osha.gov/SLTC/noisehearingconservation/index.html

White, F. A. 1975. *Our Acoustic Environment*. John Wiley & Sons. New York.

CHAPTER 23

Sound in Enclosed Spaces

CHAPTER 22 PRESENTED THE FUNDAMENTALS OF SOUND theory, the characteristics of human hearing and speech, and information on the negative effects of unwanted and excessive sounds. This chapter will discuss in some detail the interactions between an enclosed space and a sound generated within it, which is essentially the definition of room acoustics.

23.1 SOUND IN ENCLOSURES

When a continuous sound is generated in an enclosure, fields are set up as described in Section 23.7. When the sound is not a continuous tone or noise, but a series of discrete sounds following one another and containing information, as in speech or music, the room must be designed to maintain and enhance the information's intelligibility. That is what is meant by *design of room acoustics*.

Generated sound radiates out from a source until it strikes a room boundary or another large surface. Before reaching this surface, the sound intensity is attenuated by distance (see the inverse square law—Section 22.5) and by absorption in the air. The latter is appreciable only in large rooms and at frequencies above 2000 Hz. When the sound reaches a wall, it is partially reflected and partially absorbed, and a small portion is transmitted into adjoining spaces. The energy transmitted has little effect on the space within which the sound originates, although, as discussed in Chapter 24, it may be very important in the surrounding spaces.

The ratio between the energy absorbed and the energy reflected by a surface will significantly affect what one hears within a space. Specifically, if little energy is absorbed and much is reflected, two effects will be noticeable. Intermittent sounds will be mixed together (which may make speech *less* intelligible or music more pleasant), and steady sounds will accumulate into a reverberant field, making the space noisy. Conversely, if much energy is absorbed and little reflected, the room will sound quiet for speech and "dead" for music. Quantification of these two primary characteristics of an enclosed space—absorption and reverberation (echo)—is the subject of the next six sections.

ABSORPTION

23.2 SOUND ABSORPTION

When sound energy impinges on a material, part is reflected and the remainder is absorbed (in the sense that it is not reflected). Some of the "absorbed" energy is transmitted, although that part is so small that for our discussion here it will be ignored. Materials are neither perfect reflectors nor perfect absorbers. The term used to define a material's sound absorption characteristic is its *coefficient of absorption*, which is usually represented by the lowercase Greek letter alpha (α). This sound absorption coefficient is defined as

$$\alpha = \frac{I_a}{I_i} \tag{23.1}$$

where

I_a = sound power density (intensity) absorbed by the material, W/cm^2

I_i = intensity impinging on the material, W/cm^2

α = absorption coefficient, with no units since it represents a ratio

This absorption coefficient α can also be thought of as a measure of absorption effectiveness; the larger the absorption coefficient, the more effective a sound absorber the material is. Thus, an absorption coefficient of 1.0 indicates 100% absorption and zero reflection of the impinging sound energy. We have already said that no material is a perfect absorber, but an absence of material, that is, an open space, transmits (absorbs) all the impinging energy and therefore can be considered a perfect absorbing "material."

Since open space has this characteristic, α has also been defined as the ratio between the absorption of a given material and that of an *open window* of the same area. By definition, then, for an opening (open window, open door, etc.)

$$\alpha = 1.0$$

The total absorption A of a given quantity of material is proportional to its area and its absorption coefficient, that is,

$$A = S\alpha \tag{23.2}$$

where

A = total absorption, sabins

S = surface area, square feet or square meters

α = absorption coefficient

Since α is a ratio and thus unitless, and S is a unit of area, $S\alpha$ should be in units of area as well. Instead, sound absorption units are called *sabins* in honor of W. C. Sabine, a pioneer in architectural acoustics. One sabin (m^2) is the sound absorption equivalent of an open window 1 m^2 in area. Similarly, 1 sabin (ft^2) is equivalent to 1 ft^2 of open window. As expected, 1 sabin (m^2) equals 10.76 sabins (ft^2). In this text, when not otherwise specified, a sabin (ft^2) is intended.

All rooms are constructed of several materials, each having a different absorption coefficient. In addition, most rooms contain furnishings, which have their own individual coefficients of absorption. Thus, to determine the total absorption of a room, it is necessary to sum the component absorptions, that is,

$$\sum S\alpha = S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n$$

or

$$\sum A = A_1 + A_2 + \ldots + A_n \tag{23.3}$$

where

$\sum S\alpha$ = total absorption in the room, sabins

S_1, S_2, etc. = surface area of each material

α_1, α_2, etc. = absorption coefficient of each material

A_1, A_2, etc. = total absorption of each material

If S is expressed in square feet, then A is in sabins (ft^2); if S is expressed in square meters, then A is sabins (m^2).

Absorption coefficients for some common materials, sound-absorbing materials, and auditorium furnishings are tabulated in Table 23.1. It is important to note that for most common materials, absorption (and therefore α) varies with frequency. Thus, accurate absorption calculations must be made individually for the frequencies being studied.

23.3 MECHANICS OF ABSORPTION

At this point, it is appropriate to examine absorption as an acoustic phenomenon so that we may understand the use of absorptive materials. In an untreated room of normal construction (Fig. 23.1*a*), when sound waves strike the walls or ceiling, a small portion of the sound is transmitted, a small portion is absorbed, and most of it is reflected. The exact proportions depend upon the nature of the construction. When acoustical treatment is applied to the room surfaces as in Fig. 23.1*b*, some of the energy in the sound waves is dissipated before the sound reaches the wall. The transmitted portion is slightly reduced, but the reflected portion is greatly reduced.

TABLE 23.1 Octave Band Average Sound Absorption Coefficients[a]

		Absorption Coefficients (α)						
General Building Materials and Furnishings[b]		**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**NRC[c]**
Brick, unglazed		0.03	0.03	0.03	0.04	0.05	0.07	0.005
Brick, unglazed, painted		0.01	0.01	0.02	0.02	0.02	0.03	0.00
Carpet, heavy, on concrete		0.02	0.06	0.14	0.37	0.60	0.65	0.29
Carpet, heavy, on 40-oz (1.1 kg) hairfelt or foam rubber		0.08	0.24	0.57	0.69	0.71	0.73	0.55
Concrete block, coarse		0.36	0.44	0.31	0.29	0.39	0.25	0.35
Concrete block, painted		0.10	0.05	0.06	0.07	0.09	0.08	0.05
Fabrics								
Light velour, 10 oz/yd^2, hung straight, in contact with wall		0.03	0.04	0.11	0.17	0.24	0.35	0.15
Medium velour, 14 oz/yd^2, draped to half area		0.07	0.31	0.49	0.75	0.70	0.60	0.55
Heavy velour, 18 oz/yd^2, draped to half area		0.14	0.35	0.55	0.72	0.70	0.65	0.60
Floors								
Concrete or terrazzo		0.01	0.01	0.015	0.02	0.02	0.02	0.00
Linoleum, asphalt, rubber, or cork tile on concrete		0.02	0.03	0.03	0.03	0.03	0.02	0.05
Wood		0.15	0.11	0.10	0.07	0.06	0.07	0.10
Glass								
Large panes of heavy plate glass		0.18	0.06	0.04	0.03	0.02	0.02	0.05
Ordinary window glass		0.35	0.25	0.18	0.12	0.07	0.04	0.15
Gypsum board, ½ in., nailed to 2×4's, 16 in. o.c.		0.10	0.08	0.05	0.03	0.03	0.03	0.05
Marble or glazed tile		0.01	0.01	0.01	0.01	0.02	0.02	0.00
Openings								
Stage, depending on furnishings					0.25–0.75			
Deep balcony, upholstered seats					0.50–1.00			
Grilles, ventilating					0.15–0.50			
Plaster, gypsum or lime, smooth finish on tile or brick		0.013	0.015	0.02	0.03	0.04	0.05	0.05
Plaster, gypsum or lime, on lath		0.14	0.10	0.06	0.05	0.04	0.03	0.05
Plywood paneling, ⅜-in. (9-mm) thick		0.28	0.22	0.17	0.09	0.10	0.11	0.15
Rough wood, as tongue-and-groove cedar		0.24	0.19	0.14	0.08	0.13	0.10	0.14
Slightly vibrating surface (e.g., hollow core door)		0.02	0.02	0.03	0.03	0.04	0.05	0.03
Readily vibrating surface (e.g., thin wood paneling on 16-in. [406-mm] studs)		0.10	0.07	0.05	0.04	0.04	0.05	0.05
Water surface, as in a swimming pool		0.008	0.008	0.013	0.015	0.020	0.025	0.00
Absorption of Seats and Audience[d]		**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**NRC[c]**
Audience, in upholstered seats, per ft^2 of floor area		0.60	0.74	0.88	0.96	0.93	0.85	—
Unoccupied cloth-upholstered seats, per ft^2 of floor area		0.49	0.66	0.80	0.88	0.82	0.70	—
Wooden pews, occupied, per ft^2 of floor area		0.57	0.61	0.75	0.86	0.91	0.86	—
Students in tablet-arm chairs, per ft^2 of floor area		0.30	0.42	0.50	0.85	0.85	0.84	—
Acoustic Absorptive Materials	**Mtg[e]**	**125 Hz**	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**NRC[c]**
High-performance vinyl-faced fiberglass ceiling panels								
1-in. thick	E405	0.73	0.88	0.71	0.98	0.96	0.77	0.90
1.5-in. thick	E405	0.79	0.98	0.83	1.03	0.98	0.80	0.95
Painted nubby glass cloth panels								
¾-in. thick	E405	0.81	0.94	0.65	0.87	1.00	0.96	0.85
1-in. thick	E405	0.78	0.92	0.79	1.00	1.03	1.10	0.95
Random fissured ¾-in.-thick panels	E405	0.52	0.58	0.60	0.80	0.92	0.80	0.70
Perforated metal panel with infill 1-in. thick	E405	0.70	0.86	0.74	0.88	0.95	0.86	0.85
Typical averages, mineral fiber tiles and panels								
¾-in. fissured	E405	0.47	0.50	0.52	0.76	0.86	0.81	0.65
¾-in. textured	E405	0.49	0.55	0.53	0.80	0.94	0.83	0.70
⅝-in. fissured	E405	0.28	0.33	0.66	0.73	0.74	0.75	0.60
⅝-in. textured	E405	0.29	0.35	0.66	0.63	0.44	0.34	0.50
⅝-in. perforated	E405	0.27	0.29	0.55	0.78	0.69	0.53	0.60
3-in. thick × 16-in. square on 24-in. centers	A	0.40	0.61	1.92	2.54	2.62	2.60	

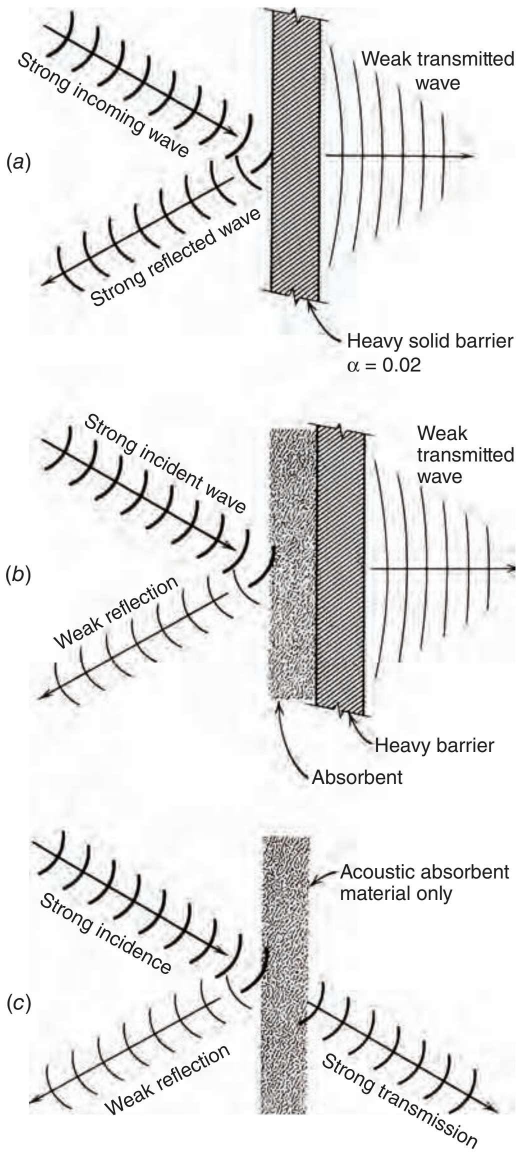
[a]This table is useful in making preliminary calculations. Complete tables of absorption coefficients for the various materials that normally constitute the interior finish of rooms may be found in books on architectural acoustics.

[b]Selected data courtesy of Owens-Corning Fiberglass.

[c]Noise reduction coefficient: the arithmetic average of the α values at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz.

[d]When the audience is randomly spaced, use an average of 5.0 sabins (ft^2) per person.

[e]See Fig. 23.4 for mounting methods.



Interactive Animation

Fig. 23.1 *(a) Action of an incoming sound wave striking a heavy barrier. Much of the energy is reflected, some is absorbed, and a little is transmitted. (b) When absorbent material is applied to a heavy wall, it "traps" sound, preventing reflection, while the wall mass acts to reduce transmission. (c) Action of acoustic absorbent material alone. Very little energy is reflected, some is absorbed, and most is transmitted.*

It is important to understand, however, that the principal effect of absorptive material is on the reflected sound. The transmitted sound energy is essentially determined by the mass of the solid airtight barrier between the two spaces. This is graphically represented in Fig. 23.1*c*. The effect of added acoustic absorption in a space is shown in Fig. 23.2 and is calculated in Section 23.9.

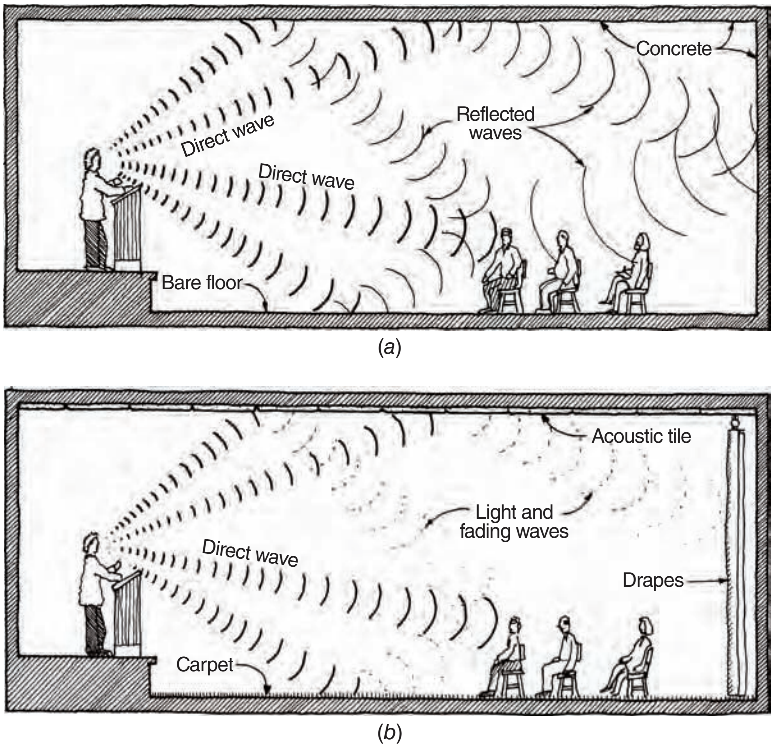
23.4 ABSORPTIVE MATERIALS

We will now examine acoustic materials and the effect of varying type, quantity, thickness, and installation methods. There are three broad families of sound absorption—fibrous materials, panel resonators, and volume resonators. All three types absorb sound by changing sound energy into heat energy. Only fibrous materials and panel resonators are used commonly in buildings. Volume resonators—also known as *Helmholtz resonators*, after their originator Hermann von Helmholtz—are used principally as devices for absorbing a narrow band of frequencies. The discussion in this section refers to fibrous absorbers; the other two types are discussed in Section 24.2.

Fibrous materials absorb acoustic energy by the frictional drag of air moving in the tiny spaces between the fibers. The absorption provided by a specific material depends upon its thickness, density, porosity, and resistance to airflow. Since the action depends upon absorbing energy by "pumping" air through the material, the air paths *must extend from one side to the other*. A fibrous material with sealed pores is almost useless as an acoustic absorbent. (Therefore, painting will generally ruin a porous absorber.) A simple test is to blow smoke through the material. If the smoke passes through freely and the material is porous, fibrous, and thick, it should be a good sound absorbent. Absorbency increases with increasing material porosity up to approximately 70% porosity; above that figure, absorbency remains fairly constant.

Table 23.1 gives absorption coefficients for fibrous absorbent materials and for some other building materials and furnishings. Several important conclusions can be drawn from examination of this table and Fig. 23.3:

1. For absorbent materials, absorption is normally higher at high frequencies than at low ones.
2. Absorption is not always proportional to thickness, but depends upon the type of material used and the method of installation (see Fig. 23.3). It is clear from this figure that beyond a nominal thickness, little is to be gained by additional thickness except at very low frequencies, or



Interactive Animation

Fig. 23.2 *In an untreated space (a) reverberant (reflected) sound constitutes a large portion of received sound in much of the room. These reflections are largely eliminated in (b) by wall and ceiling absorption. Note that direct wave sound is completely unaffected.*

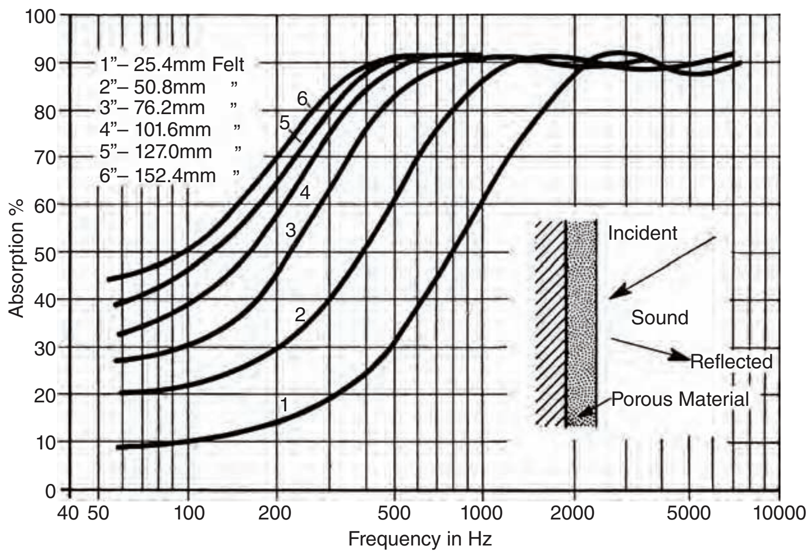


Fig. 23.3 *Variation of the absorption coefficient with the thickness of felt absorbent. Note particularly that beyond 1 kHz, all thicknesses give the same α, whereas at low frequencies absorption is proportional to thickness. Note also that a very heavy layer is required to give appreciable absorption at low frequency. (Courtesy of Brüel and Kjær.)*

when material is installed discontinuously, as described in the next item.

3. It is possible to obtain effective α values greater than 1.0 by using very thick blocks. Because they are installed at a distance from each other, and their edge absorption is very large (particularly at high frequencies), they exhibit α greater than 1.0.
4. Installation methods have a pronounced effect, as discussed in the following section.
5. All other factors remaining constant, the thicker an absorbent material, the better its low-frequency absorption.

23.5 INSTALLATION OF ABSORPTIVE MATERIALS

Coefficient ratings for absorptive materials are always given with respect to mountings corresponding to ASTM (American Society for Testing and Materials) (ASTM, 2000) requirements. The most common standardized mounting methods are shown in Fig. 23.4. Installation of absorbent material directly on a wall or ceiling is the least effective means, since exposure to sound energy is minimal. When an air gap is left between the porous layer and the rigid surface, the combination acts almost as well in midfrequencies as an absorbent layer equivalent in thickness to the air plus the porous material (Fig. 23.5). One problem with this technique, however, is that at the $\lambda/2$ node of a standing wave there is a severe drop in absorption, as can be seen in Fig. 23.5*c*. At 1000 Hz, one-half wavelength is approximately 7 in. (178 mm). At that distance, α drops severely but is a maximum at $\lambda/4$ or 3.5 in. (89 mm).

For ceiling tile hung at 16 in. (405 mm) below the slab (Fig. 23.4, type E 405 mounting method), the drop in absorption occurs at

$$\lambda/2 = 16 \text{ in. } (405 \text{ mm})$$

$$\lambda = 32 \text{ in.} = 2.67 \text{ ft } [810 \text{ mm}]$$

$$f = \frac{1128}{2.67} = 422 \text{ Hz}$$

which is midfrequency. This factor should be considered in applying absorptive material. Avoid a spacing corresponding to a drop in absorption at a sensitive frequency. To obtain good low-frequency absorption, it is essential that a deep air space be provided behind the absorbent material and that walls be treated in addition to the ceiling.

In increasing order of effectiveness, absorbent material can be applied:

1. Directly to the room surface
2. Hung below the ceiling and supported away from the walls
3. Hung from the ceiling as louvers or baffles
4. Made up into shapes such as cubes or tetrahedrons and suspended from the ceiling

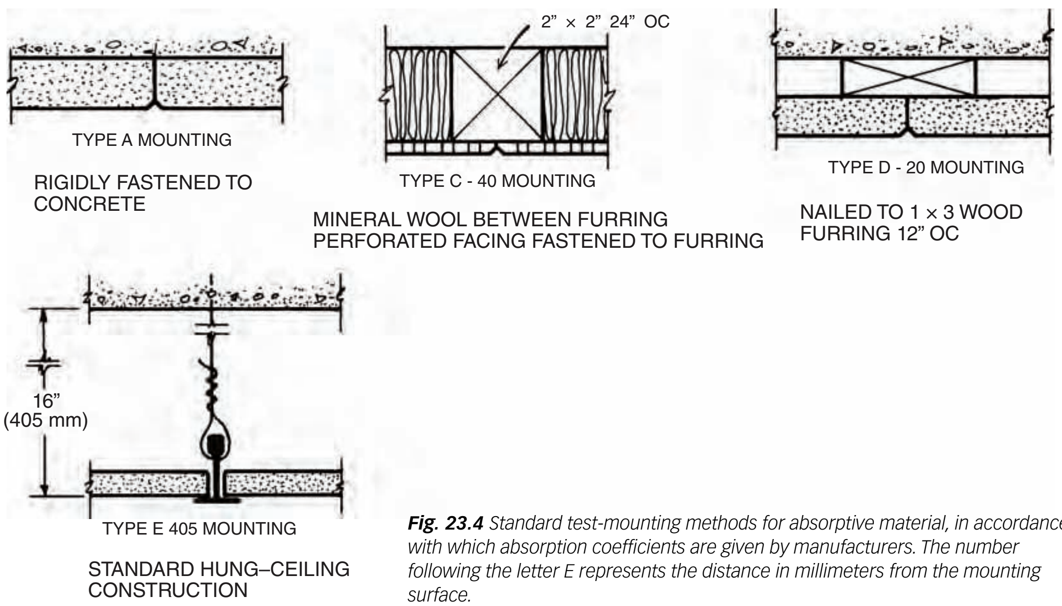


Fig. 23.4 *Standard test-mounting methods for absorptive material, in accordance with which absorption coefficients are given by manufacturers. The number following the letter E represents the distance in millimeters from the mounting surface.*

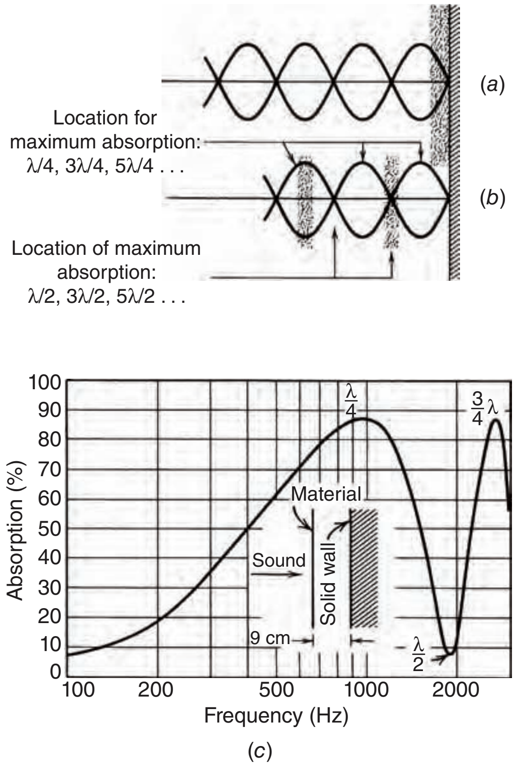


Fig. 23.5 *Sound waves striking a surface of a large mass will create standing waves at certain frequencies (a), depending upon the room dimensions. Only insulation placed at the peaks (b) of these waves (λ/4, 3λ/4...) is effective, as seen in (c). (Part c reproduced with permission of Brüel and Kjær.)*

The last two techniques are extremely effective because they expose a very large surface of porous material—much larger than could be obtained with wall or ceiling covering. Of course, these suspended objects become architectural elements and must be handled accordingly. In contrast, surface coverings are relatively architecturally neutral. In general, treatment should not be limited to one room surface such as the ceiling. All three principal surfaces in the direction of sound propagation—that is, the ceiling, floor, and back wall—should be treated *approximately equally* for best results. The common practice of treating the ceiling only is generally inadvisable, since high frequencies are highly directive and may not reach the ceiling until the third reflection.

In order to fully understand the effects of absorbent materials in an enclosed space, it is necessary to introduce two new concepts: *reverberation* and *sound fields*. This will be done in the next two sections, after which we will return to our discussion of the use and effects of acoustic absorptive material in enclosed spaces.

ROOM ACOUSTICS

23.6 REVERBERATION

Reverberation is the persistence of sound after the sound source has ceased. Such persistence is a result of repeated reflections in an enclosed space. Reverberation time (T_R) is defined as the time required for the sound level to decrease 60 dB after the source has stopped producing sound. For rooms of usual size and shape, the reverberation time at a specific frequency may be found by the formula

$$T_R = K \times \frac{V}{\sum A} \text{ seconds} \tag{23.4}$$

where

K = a constant, equal to 0.05 when measurements are in feet and 0.16 when in meters
V = room volume, ft^3 or m^3
$\sum A$ = total room absorption, sabins (ft^2 or m^2) at the frequency in question

(For spaces of unusual shapes, see Beranek, 1988.) Reverberation is one of the most pronounced hearing reactions in an enclosed space. It is the ear's reaction to echoes, giving a subjective impression of "liveness" or "deadness" to a space.

A space with highly reflective surfaces, and therefore a low average absorption coefficient ($\bar{\alpha} < 0.2$), sounds live. Conversely, a highly absorptive nonreflective environment ($\bar{\alpha} > 0.4$) sounds dead. ($\bar{\alpha}$ is the average absorption coefficient of the entire space, as explained in detail in Section 23.8.) Since room absorption is related to total surface area, which in turn is related by room proportions to room volume, it is possible to relate all three factors in a single diagram. Figure 23.6 is drawn using room proportions of 2:1.5:1, for L:W:H, based on Fig. 23.22 for preferred room proportions. These proportions (2:1.5:1) represent the average of the extremes of Fig. 23.22. The maximum differential

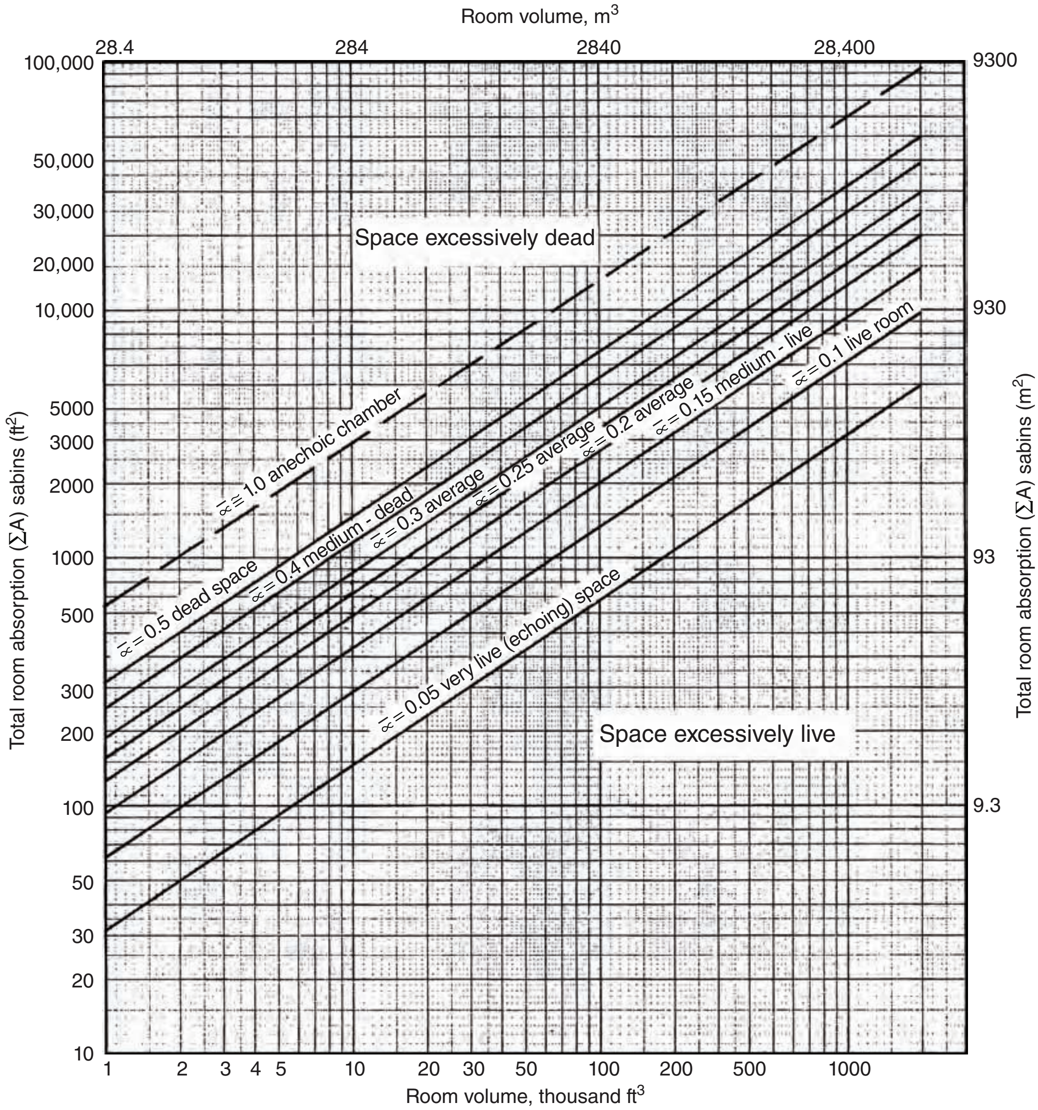


Fig. 23.6 *Chart indicating a room's "liveness" as a function of its volume and total sabin absorption. The L:W:H room proportions chosen—2H:1.5H:H—represent the average of the three extreme points of the recommended room proportion triangle in Fig. 23.22. For these proportions,* $S = 6.25\ V^{2/3}$ *and therefore* $A = S\ \bar{\alpha} = 6.25\ \bar{\alpha}\ V^{2/3}\ \bar{\alpha}$.

introduced by using average proportions is 2.5%—well within engineering accuracy.

The ultimate dead space is one where there is no reflection at all—as is the case outdoors in a flat open area. Indoors, we receive an auditory cue in the form of reflected sound (feedback) that helps us regulate our sound power output (voice level). Outdoors, the absence of this cue, to which we are so accustomed by our largely indoor existence, automatically causes us to raise our output. For this reason, most people tend to speak excessively loudly outdoors. Conversely, a highly reflective indoor condition gives a large feedback signal, which usually results in lowered vocal output.

In common room acoustics studies, reverberation times are calculated at 125 Hz, 500 Hz, 1000 Hz, and 2000 Hz. The midfrequency (500 Hz to 1000 Hz) range is generally the reference used in specifying the reverberation time of a room when studying the speech characteristic of the space.

Reverberation can be considered as a mixture of previous and more recent sounds. The converse of *reverberation* or *reverberance* is *articulation*. An articulate environment keeps each sound event separate rather than running them together. Spaces for speech activities should be less reverberant—more articulate—than those designed for performance of music. See Sections 23.11 and 23.12 for reverberation criteria for speech and music rooms, respectively.

23.7 SOUND FIELDS IN AN ENCLOSED SPACE

The inverse square law described in Section 22.5 holds true for the acoustic *far field*, which is a sound field sufficiently far from a source that intensity is proportional to power and inversely proportional to distance. This type of acoustic field is developed in open, obstruction-free space. Propagation in an enclosed space is quite different. There, when a sound reaches a wall or another large (with respect to wavelength) obstruction, part of the sound energy is reflected and part absorbed. As a result, the sound at any point in the room is a combination of direct sound from the source plus reflected sound from walls and other obstructions. If the reflections are so dominant that the sound level becomes uniform throughout the room, the acoustic field within the room is termed a *diffuse* one (no shadows), and intensity measurements with respect to a specific source are meaningless. Of course, if it is our intention to measure sound pressure level at a specific point, such as a seat in an auditorium, the type of acoustic field in the room is irrelevant.

Most indoor spaces do not have such a high level of reflection that a diffuse field is created. Instead, there is a *near field* near the source, a *free field* beyond the near field, and a *reverberant field* near the walls (Fig. 23.7). These can be recognized as follows:

1. The *near field* is generally within one wavelength of the lowest frequency of sound produced by the source. Within this distance, sound pressure level measurements vary widely and are not meaningful. (The maximum wavelength for the human male voice is about 11 ft [3.4 m].)
2. Close to large obstructions such as walls, the *reverberant field* is dominant and approaches a diffuse condition. In well-designed music auditoriums, the reverberant (diffuse) field predominates, and the sound pressure level remains relatively constant beyond the free field area.
3. The *free* (far) *field* exists between the near and reverberant fields, and there intensity varies directly with pressure and inversely with distance squared. In this field, sound pressure level drops 6 dB with each doubling of distance from the source, and it is in this field that meaningful sound pressure level measurements can be made with respect to a specific small source.

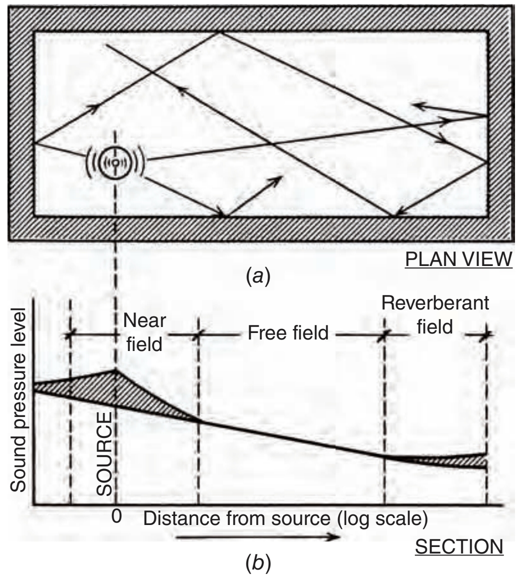


Fig. 23.7 *The type of sound field in an enclosed space depends largely on reflections (reverberation) and absorption. In a typical room there is a near field adjacent to the sound, a free field beyond that, and a reverberant field adjacent to the walls. In a large hall or auditorium, the reverberant field dominates, and the sound pressure level is approximately constant.*

23.8 SOUND POWER LEVEL AND SOUND PRESSURE LEVEL

Sound *power level* (PWL) is a measure of the amount of sound generated by a source, independent of its environment. Sound *pressure level* (SPL) can be thought of as the noise or sound in an enclosed space resulting from a source in that space, as affected by the characteristics of the space and the position of the listener. It is thus an end effect.

Since it is desirable to be able to predict the SPL in a space during the design stage, *before* construction, and also because of the difficulty of SPL measurement *after* construction, in rooms with various types of sound fields (as explained in Section 23.7), it is useful to have equations and/or a graphic means of relating PWL to SPL. PWL data are supplied by manufacturers of equipment referenced to either octave or one-third octave bands. In free space, SPL and PWL are simply related by the inverse square law, whereas in enclosed spaces the room characteristics come into play. Roughly speaking, an analogy to lighting can be drawn: SPL corresponds to illuminance (that is, footcandles or lux), and PWL corresponds to the lumen output of the source causing the illuminance.

The basic relationship between SPL and PWL for a single small source in a room large enough to have both free and reverberant fields is:

I-P units:

$$SPL = PWL + 10 \log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) + 10.5 \qquad (23.5)$$

SI units:

$$SPL = PWL + 10 \log\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) + 0.2 \qquad (23.6)$$

where

Q = is a directivity constant
SPL = sound pressure level, dB
PWL = sound power level, dB
r = distance from source, ft (m)
R = room factor, ft^2 (m^2)

The factor R can be calculated from

$$R = \frac{\sum S\bar{\alpha}}{1-\bar{\alpha}}$$

where

$\sum S$ = total room surface area, ft^2 (m^2)
$\bar{\alpha}$ = average absorption coefficient of all materials in the room

that is,

$$\bar{\alpha} = \frac{\sum A \text{ (total room absorption)}}{\sum S \text{ (total room surface area)}} \qquad (23.7)$$

or

$$\bar{\alpha} = \frac{S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n}{S_1 + S_2 + \cdots + S_n} \qquad (23.8)$$

The directivity constant Q is either inherent in the sound source, and as such will be part of the given data, or can be obtained from Fig. 23.8 for a nondirectional source made directional by adjacent reflecting surfaces.

Thus, for a source suspended or supported at least ½ wavelength (at its lowest frequency) from a ceiling or floor, $Q = 1$; a source near a floor and distant from the walls relates to $Q = 2$; and so on. In a space containing more than one sound source, the SPLs can be combined as explained in Section 22.5. In the two extreme cases (i.e., rooms with only far [direct] fields and rooms with only reverberant [diffuse] fields, corresponding to dead and live rooms, respectively) for a nondirectional source located on the floor and away from walls ($Q = 2$), Equations 23.5 and 23.6 reduce to:

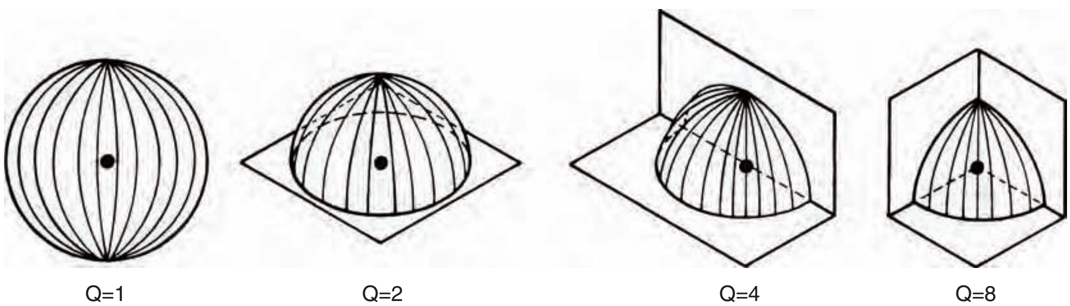


Fig. 23.8 *Diagrams illustrating directivity factors for either inherently directive sources or nondirective sources placed adjacent to large reflecting surfaces. (Courtesy of Barry Blower Co.)*

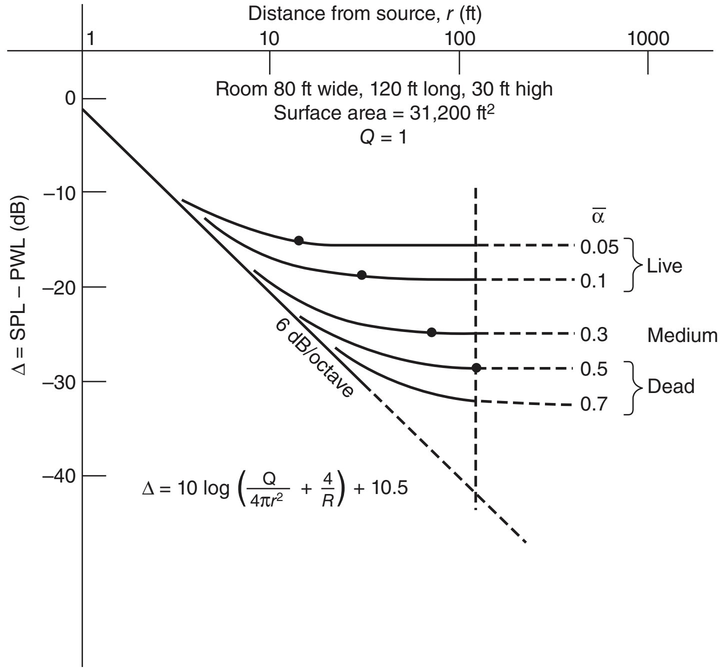


Fig. 23.9 *Calculated curves show that the development of a reverberant field (constant SPL, or flat curve) is dependent upon a room's absorption characteristics. On each curve, the point at which a reverberant field begins is indicated by a dot on the curve. In a live room ($\bar{\alpha}$ = 0.1), the reverberant field begins 20 ft (6.1 m) from the source. In a dead room ($\bar{\alpha}$ = 0.5), it begins 120 ft (36 m) from the source, that is, at the back wall. Effectively, then, there is no reverberant field in such a room (or in any room with $\bar{\alpha}$– = 0.5). The slope of the asymptote is 6 dB per octave, that is, inverse square attenuation.*

Dead room, direct field:

I-P units:

$$\begin{aligned} SPL &= PWL - 20 \log r + (Q - 0.6) \\ &= PWL - 20 \log r + 1.4 \end{aligned} \qquad (23.9)$$

SI units:

$$\begin{aligned} SPL &= PWL - 20 \log r + (Q - 10.9) \\ &= PWL - 20 \log r - 8.9 \end{aligned} \qquad (23.10)$$

Live room, diffuse-reverberant field:

I-P units:

$$SPL = PWL - 10 \log \sum A + 16.3 \qquad (23.11)$$

SI units:

$$SPL = PWL - 10 \log \sum A + 6.0 \qquad (23.12)$$

To understand the effect of room absorption on the development of the reverberant field in a large space, refer to Fig. 23.9. The field is plotted from Equation 23.5, for a room 80 ft × 120 ft × 30 ft high (24.4 × 36.6 × 9.1 m), using average absorptions ($\bar{\alpha}$) ranging from 0.05 to 0.7, that is, from very live to very dead. Note particularly that the addition of sufficient absorbent material can, by drastically reducing sound reflections from room surfaces, entirely prevent the development of a reverberant (diffuse) field. This is particularly important in noisy industrial interiors where the building materials commonly employed are generally nonabsorbent, and the noise sources are both numerous and loud. An example of the use of absorptive material to effect a considerable degree of in-room noise reduction is demonstrated in the next section. We emphasize that the effect is almost exclusively in the room where the absorptive material is used, since the acoustic energy transmitted to adjacent spaces is only minimally affected. Sound transmission from one enclosed space to an adjoining space through a common barrier depends almost entirely upon the type of barrier. This is discussed in detail in Chapter 24.

23.9 NOISE REDUCTION BY ABSORPTION

Equation 23.6 relates SPL and PWL as a function of distance from the source and room absorption. The following example shows the application of this equation and the result of adding absorption to the space.

EXAMPLE 23.1 An open blower is installed on the floor, away from the walls, in a large enclosed space that is 6 m (20 ft) long, 12 m (39 ft) wide, and 4 m (13 ft) high. The floor is concrete (α = 0.01); the walls and ceiling are painted block ($\alpha = 0.07$). The PWLs supplied by the manufacturer are 90 dB at 500 Hz and 87 dB at 2000 Hz. Calculate the SPL at distances of 5 m and 10 m (16.4 and 32.8 ft) from the blower outlet: (a) in the original room, (b) with double the absorption, and (c) with quadruple the absorption.

SOLUTION

1. From Equation 23.6, we have the expression

$$SPL = PWL + 10\log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) + 0.2$$

In our example, $Q = 2$ (see Fig. 23.8).

2. The first step is to calculate the room factor R for the three absorption situations (a, b, and c).

$$R = \frac{S\bar{\alpha}}{1-\bar{\alpha}}$$

$S = 2(48) + 2(24) + 2(72) = 288\ \text{m}^2\ [3100\ \text{ft}^2]$

From Equation 23.8:

$$\bar{\alpha}\ \text{original} = \frac{(144)(0.07) + (72)(0.07) + (72)(0.01)}{288} = 0.055$$

$\bar{\alpha}_a = 0.055$ $\quad R_a = 16.76$
$\bar{\alpha}_b = 2(0.055) = 0.11$ $\quad R_b = 35.6$
$\bar{\alpha}_c = 4(0.055) = 0.22$ $\quad R_c = 81.23$

3. Calculating SPL values and tabulating, we obtain

	500 Hz		2000 Hz	
SPL for:	**5 m**	**10 m**	**5 m**	**10 m**
(a) Original room	84.1	84.0	81.1	81.0
(b) Double $\bar{\alpha}$	81.0	80.8	78.0	77.8
(c) Quadruple $\bar{\alpha}$	77.7	77.3	74.7	74.3

The results indicate the very important fact that *doubling the absorption decreases the noise sound pressure level by only 3 dB*. Therefore, it requires a quadrupling of absorption to make the decrease noticeable (see Table 22.3). This is an expensive procedure with diminishing returns.

If the entire space is considered to be a reverberant field, then from Equation 23.11 the sound intensity level (IL) can be expressed as follows:

$$IL = PWL - 10\log\sum A + 16.3\ \text{dB} \qquad (23.13)$$

where

$\sum A$ = total absorption in room, sabins (ft^2)
IL = intensity level, dB
PWL = sound power level, dB

Although increasing absorption decreases the sound/noise level, the level cannot be reduced below the free field level for that distance from the source because the free field situation corresponds to outdoors, where $\bar{\alpha} = 1.0$.

The amount of noise reduction provided by additional absorption may be determined by noise reduction (NR):

$$NR = IL_1 - IL_2 = 10\log\sum A_2 - 10\log\sum A_1$$

Therefore,

$$NR = 10\log\frac{\sum A_2}{\sum A1} \qquad (23.14)$$

where

NR = noise reduction, dB
$\sum A_2$ = total absorption, final condition
$\sum A_1$ = total absorption, initial condition

From Equation 23.14 it is seen that doubling the absorption results in a noise reduction of 3 dB, since $10\log_{10} 2 = 3$ (dB). ■

It is of interest to work out a practical example using Equations 23.13 and 23.14 and compare the results with the more precise relation given in Equation 23.5.

EXAMPLE 23.2 Referring to Fig. 23.10, calculate the original sound level and the subsequent noise reduction by three steps of sound absorption treatment, assuming a completely reverberant field in the space, that is, SPL independent of location. Data:

Original condition: Painted concrete block chamber,

10 ft × 10 ft × 10 ft (approximately 3 m × 3 m × 3 m)

Fan sound power level:

At 500 Hz = 88 dB
At 2000 Hz = 78 dB

SOLUTION

Frequency (Hz)	Area (ft^2)	α	Total Absorption ($\sum S\alpha$)
500	600	0.06	36 sabins (ft^2)
2000	600	0.09	54 sabins (ft^2)

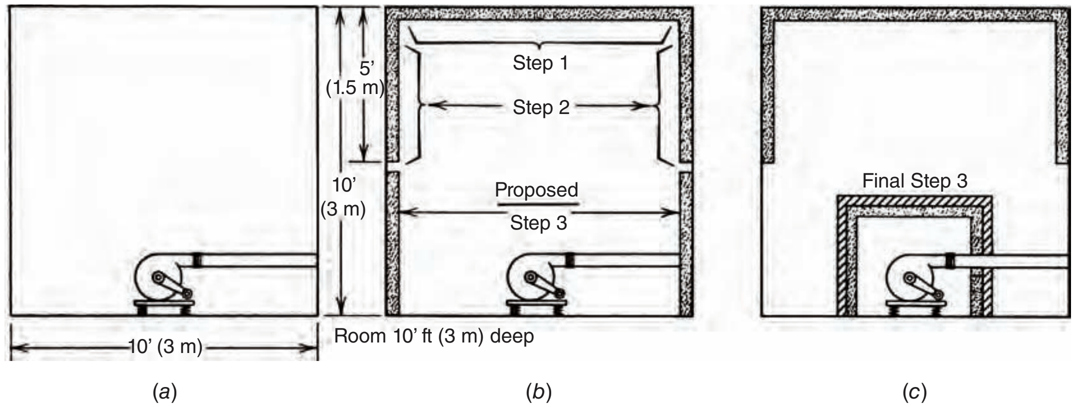


Fig. 23.10 *Quieting a room (a) by addition of absorptive material is cost-effective only through Step 2 (b). Further quieting would be accomplished locally (c), which might obviate the necessity for wall treatment (Step 2). Ceiling treatment should remain.*

a. Sound intensity level before treatment

At 500 Hz:

$$\begin{aligned} IL &= \text{sound power level} - 10 \log \sum A + 16.3 \text{ dB} \\ &= 88 \text{ dB} - 10 \log 36 + 16.3 \text{ dB} \\ &= 88 \text{ dB} - 15.6 \text{ dB} + 16.3 \text{ dB} \\ &= 88.7 \text{ dB} \end{aligned}$$

At 2000 Hz:

$$\begin{aligned} IL &= 78 \text{ dB} - 10 \log 54 + 16.3 \text{ dB} \\ &= 78 \text{ dB} - 17.3 \text{ dB} + 16.3 \text{ dB} \\ &= 77 \text{ dB} \end{aligned}$$

b. Ceiling treatment only

At 500 Hz:

$$\alpha = 0.82$$

$$\begin{aligned} \text{additional absorption} &= 100\,(0.82 - 0.06) \\ &= 76 \text{ sabins} \end{aligned}$$

$$\begin{aligned} NR &= 10 \log \frac{76+36}{36} \\ &= 4.9 \text{ dB} \end{aligned}$$

At 2000 Hz:

$$\alpha = 0.94$$

$$\Delta A = 100\,(0.94 - 0.09) = 85$$

$$\begin{aligned} NR &= 10 \log \frac{85+54}{54} \\ &= 4.1 \text{ dB} \end{aligned}$$

c. Ceiling and half-wall treatment

At 500 Hz:

$$\begin{aligned} \text{added absorption} &= 300\,(0.82 - 0.06) \\ &= 228 \text{ sabins} \end{aligned}$$

$$\begin{aligned} NR &= 10 \log \frac{228+36}{36} \\ &= 8.7 \text{ dB} \end{aligned}$$

At 2000 Hz:

$$\begin{aligned} \text{added absorption} &= 300\,(0.94 - 0.09) \\ &= 255 \text{ sabins} \end{aligned}$$

$$\begin{aligned} NR &= 10 \log \frac{255+54}{54} \\ &= 7.5 \text{ dB} \end{aligned}$$

d. Ceiling and full-wall treatment

At 500 Hz:

$$\begin{aligned} \Delta A &= 500\,(0.82 - 0.06) \\ &= 380 \text{ sabins} \end{aligned}$$

$$\begin{aligned} NR &= 10 \log \frac{380+36}{36} \\ &= 10.6 \text{ dB} \end{aligned}$$

At 2000 Hz:

$$\begin{aligned} \Delta A &= 500\,(0.94 - 0.09) \\ &= 425 \text{ sabins} \end{aligned}$$

$$\begin{aligned} NR &= 10 \log \frac{425+54}{54} \\ &= 9.5 \text{ dB} \end{aligned}$$

Summary

	IL (SPL)[a]	
	500 Hz	**2000 Hz**
Bare room	88.7	77
Ceiling treatment	−4.9 dB	−4.1 dB
	(−4.9)[a]	(−4.2)[a]
Half-wall treatment	−8.7 dB	−7.5 dB
	(−8.7)[a]	(−7.7)[a]
Full-wall treatment	−10.6 dB	−9.5 dB
	(−10.7)[a]	(−9.6)[a]

[a] The numbers in parentheses are the SPL differences as calculated from Equation 23.5 using $Q = 2$ and $r = 5$ ft (1.5 m).

Two important conclusions can be drawn from these results:

1. The third step of adding absorptive material is not worthwhile since negligible additional room quieting is accomplished. This clearly demonstrates the law of diminishing returns as applied to room quieting with absorptive materials. Starting with a live room, the initial application is effective. Beyond that, additional quieting by absorption is not economical, and the same outlay would be better used in quieting the machine itself, probably with a machine enclosure, as indicated in Fig. 23.10.
2. If we compare the figures in parentheses that resulted from a full calculation (Equation 23.5) to those arrived at using the much simpler equations applicable only to a fully diffuse field (Equation 23.11), we see that the differences are negligible. This means that the shortcut method can always be used in preliminary calculations and frequently for final results as well. The diffuse (reverberant) field calculation also lends itself nicely to a graphical solution.

Using the diffuse field Equation 23.11:

$$SPL = PWL - 10 \log \sum A + 16.3$$

and remembering that reverberation time is expressed in terms of total absorption and room volume, that is,

$$T_R = \frac{KV}{\sum A} \qquad (23.15)$$

where K is 0.05 when room volume is in cubic feet and 0.16 when it is in cubic meters. Using these equations, we can then rewrite Equations 23.11 and 23.12 in terms of reverberation time and room volume:

For room volume in ft^3:

$$SPL - PWL = -10 \log \frac{0.05V}{T_R} + 16.3 \qquad (23.16)$$

For room volume in m^3:

$$SPL - PWL = -10 \log \frac{0.16V}{T_R} + 6.0 \qquad (23.17)$$

These two equations are plotted graphically in Figs. 23.11 and 23.12. The charts are accurate for live-room, diffuse (reverberant) fields and provide a close approximation for other situations. An illustrative example will demonstrate the use of the charts. ■

EXAMPLE 23.3 A generator in a 14,000-ft^3 (396-m^3) room has a PWL of 95 dB (re: 10^{-12} W) at 400 Hz.

a. Using the chart in Fig. 23.11, find the SPL at that frequency. Assume that the sound field in the room is reverberant. The room's reverberation time is 1.0 s at 400 Hz.

b. Check the result using the chart in Fig. 23.12.

SOLUTION

a. I-P units: Enter the chart in Fig. 23.11 at 14,000 ft^3 and draw a vertical line until it intersects the 1.0-s sloping line. Extend a line from that intersection point to the X-axis and read −12 dB.

Then, since

$$SPL - PWL = -12 \text{ dB}$$

and PWL is given as 95 dB,

$$SPL = 95 - 12 = 83 \text{ dB}$$

b. SI units: The room volume is equal to 400 m^3, within engineering design accuracy (it is actually 396 m^3). Enter the chart in Fig. 23.12 at 400 m^3, and extend a line upward to T_R of 1 s and left to the X-scale. Read −12 dB. The two answers check, as they should. ■

23.10 NOISE REDUCTION COEFFICIENT

The last column in Table 23.1 is labeled NRC—noise reduction coefficient. This figure is the arithmetic average of the absorption coefficients at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. The name is ill chosen inasmuch as it cannot be used directly for noise control efforts, as the words seem to imply. It is simply useful as a single-number indicator of the midband effectiveness of a porous absorber. For critical acoustical

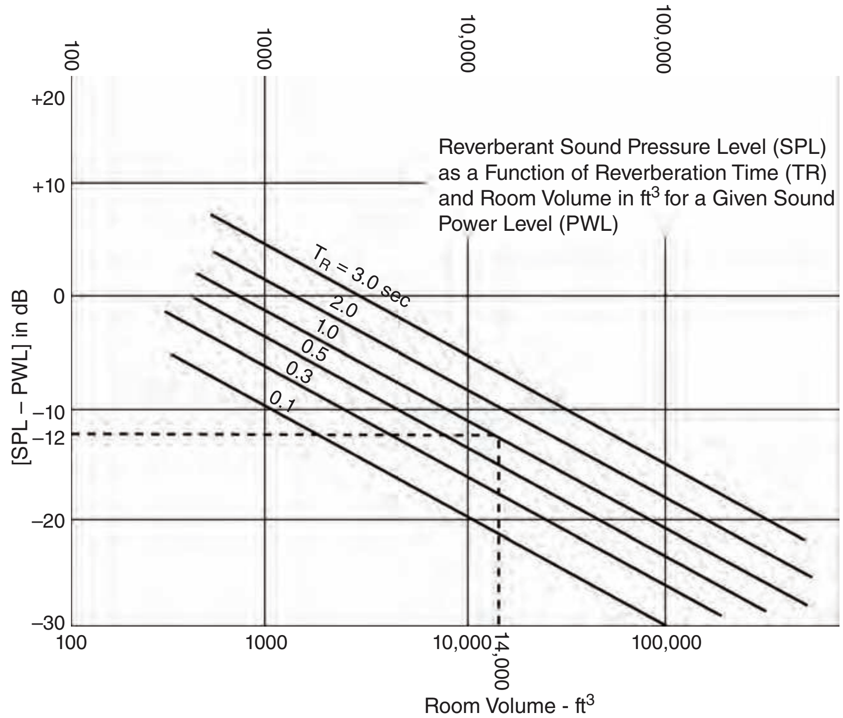


Fig. 23.11 *I-P chart for determining the reverberant sound pressure level (SPL) when the sound power level (PWL) of an item of equipment is known. Room volume in cubic feet and reverberation time in seconds are the variables.*

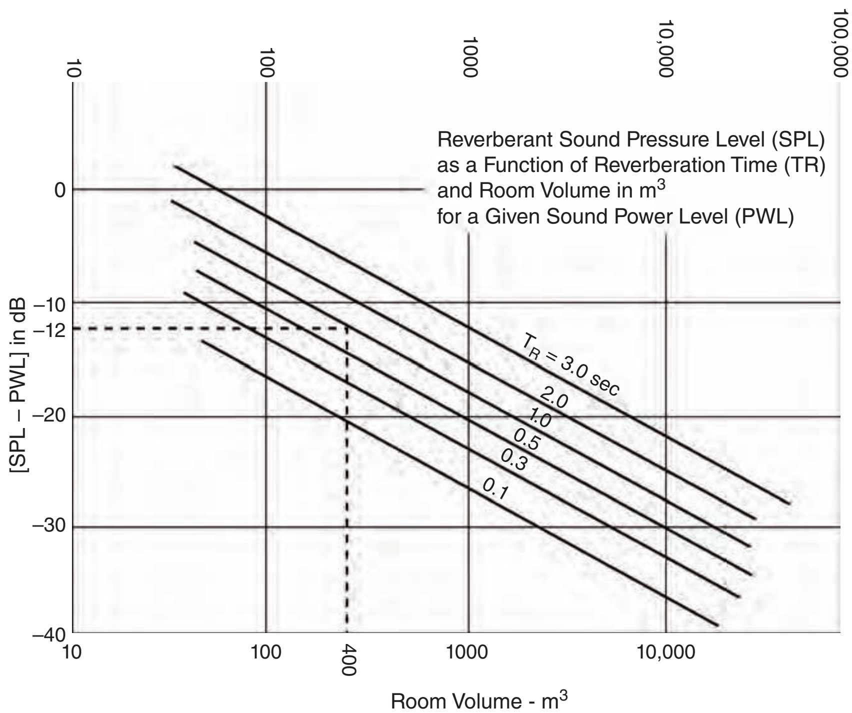


Fig. 23.12 *SI chart for determining the reverberant sound pressure level (SPL) when the sound power level (PWL) of an item of equipment is known. Room volume in cubic meters and reverberation time in seconds are the variables.*

situations, or if high- and low-end frequencies are of interest, NRC is nearly useless, and detailed analysis of absorption over the entire frequency range must be made. Two materials with the same NRC can perform quite differently, since NRC is an average, and few materials have a flat absorption characteristic. Losing sight of such a difference by reliance upon NRC is not a good move. Even more importantly, sound absorption is not the same as noise reduction. An acoustical ceiling tile, which exhibits high sound absorption, is a poor noise control barrier.

ROOM DESIGN

23.11 REVERBERATION CRITERIA FOR SPEECH ROOMS

The overriding criterion for speech is intelligibility. Since speech consists of short, disconnected sounds 30 to 300 ms in length (see Section 22.4), among which are high-frequency, low-energy phonemes, the ideal room must ensure the ear's undistorted reception of these phonemes. This requires keeping reverberation to a minimum. We can obtain a good approximation of the subjective feeling of liveness of a room, for purposes of speech, from the relation

$$T_R \text{ (speech)} = 0.3 \log \frac{V}{10} \qquad (23.18)$$

where

T_R (speech) = optimum reverberation time in seconds, for speech

V = room volume, m^3

For instance, a typical classroom might have a volume of 150 m^3 (5300 ft^3). Optimum reverberation time is

$$T_R = 0.3 \log 15 = 0.35 \text{ s}$$

Reverberation times longer than this would sound live, shorter ones dead and flat. Indeed, an increase of 20% in reverberation time would make the room excessively live and "boomy" and would negatively affect speech intelligibility. Figure 23.13 gives *optimum* midfrequency reverberation times as

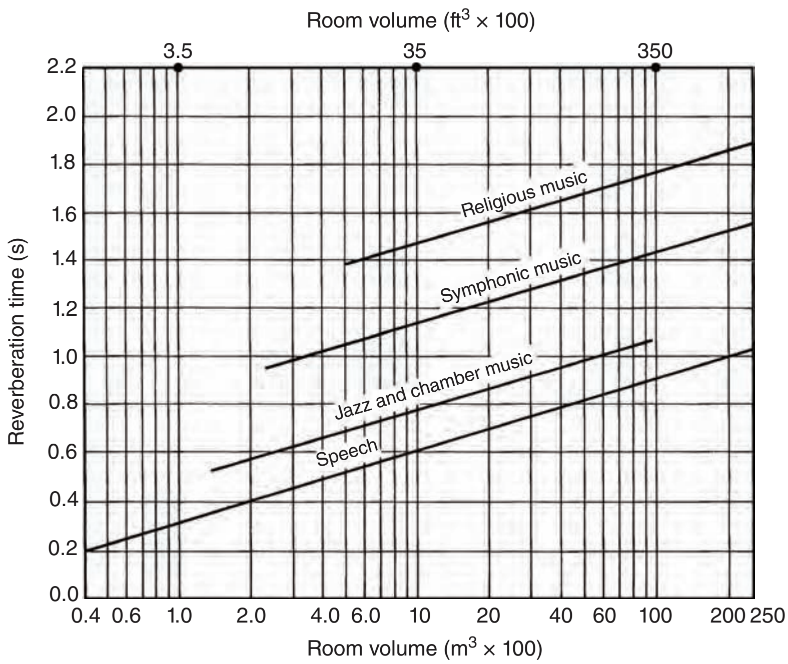


Fig. 23.13 *Optimum reverberation times for the frequency range 500 to 1000 Hz as a function of room volume. (The cubic foot volume figures are based upon the approximate conversion factor of 35 ft^3/m^3). (Reprinted by permission from E. B. Magrab. 1975.* Environmental Noise Control. *John Wiley & Sons, Hoboken, NJ, p. 206.)*

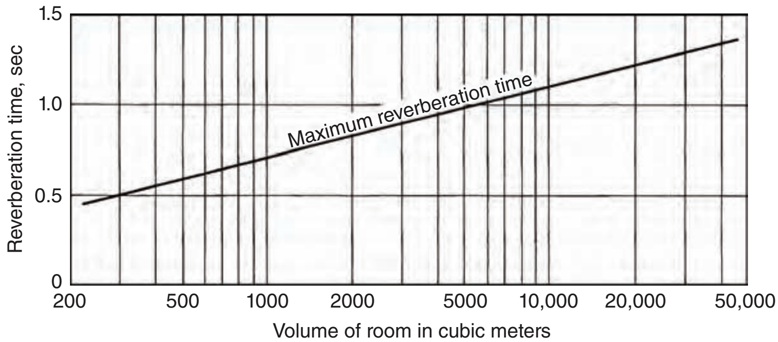


Fig. 23.14 *Maximum recommended reverberation time for speech in auditoriums and lecture halls. (From P. V. Brüel. 1951.* Sound Insulation and Room Acoustics*. Chapman & Hall, London.)*

a function of room size and use. Figure 23.14 gives *maximum* reverberation times for speech in large rooms. For good speech intelligibility, reverberation time should remain essentially flat down to 100 Hz.

The reflected sounds associated with reverberation can have either a salutary or a deleterious effect. The ear cannot distinguish between sounds that arrive within a maximum of 50 ms (1⁄20 s) of each other (some authorities use 40 ms, i.e., 1⁄25 s). Sounds arriving within this time *reinforce* the direct-path signal and appear to come from the source. Sounds arriving after this time are apprehended as a fuzzy echo or elongation of the sound, reducing intelligibility and directivity.

Since the range of 40 to 50 ms corresponds at 1128 fps (344 m/s) to 45 to 56 ft (13.7 to 17.2 m), a speech room should be so arranged that the difference between the first reflection path and the direct path is no greater than 56 ft (around 17 m), and preferably 46 ft (14 m) or less at midfrequency (Fig. 23.15). For more details concerning this and related factors on reflected paths, refer to Section 23.13.

Too *low* a reverberation time (very high absorption, minimum reflection) is also undesirable because:

1. It limits the size of the room to that which can be covered by direct sound only.
2. It is disturbing to the speaker, since absence of reflection prevents him or her from gauging the proper voice level, which tends to cause excessive effort (shouting, as when outdoors).

Thus, proper design of a room for speech is a compromise between the need for some reflection and the desire to minimize reflection to preserve intelligibility.

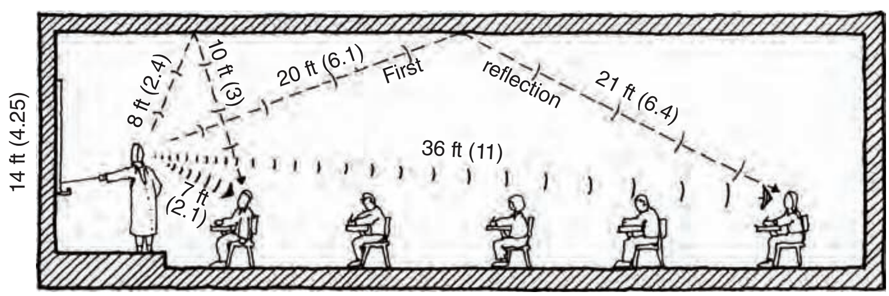


Fig. 23.15 *Sound paths in a typical medium-sized lecture room. Note that for both extremes of listener position, the maximum path-length difference between direct and first reflection is 11 ft (3.4 m). Thus the signal is reinforced, and intelligibility should be excellent if room absorption is provided to limit reverberation time to about 0.5 second maximum (see Fig. 23.14). Numbers in parentheses are dimensions in meters.*

23.12 CRITERIA FOR MUSIC PERFORMANCE

Adequate design for a music space requires recognition of the following:

1. Large-volume spaces require direct-path sound reinforcement by reflection.
2. Relatively long reverberation time is needed to enhance the music—the exact amount depending upon the type of music (Figs. 23.13 and 23.16). Designers should keep in mind that reverberation time recommendations vary as much as 100% among respected sources.
3. It is generally agreed that reverberation time should vary inversely with frequency (i.e., T_R should be longer at lower frequencies [than the midfrequency recommendation] and shorter at higher frequencies). The longer T_R at low frequencies adds fullness to music and "body" to speech. Thus, T_R at 100 Hz should be, according to most researchers, 35% to 75% longer than T_R at the center frequencies.
4. Short T_R at upper frequencies adds directivity to the music. With large ensembles, directivity gives the sense of depth and instrument location necessary for proper appreciation. This is often referred to as *clarity* or *definition* in music. With a solo instrument, this problem is diminished.
5. Brilliance of tone is primarily a function of high-frequency content. Since these frequencies are most readily absorbed, a good direct path must exist between sound source and listener. Since our eyes and ears are close together, a good sound path exists when a good vision path exists. At the other end of the spectrum, lack of sufficient bass expresses itself as a loss of "fullness," which is often caused by resonant absorption.

The actual design of a music performance space is a very complex procedure involving extensive calculations of absorption, reverberation

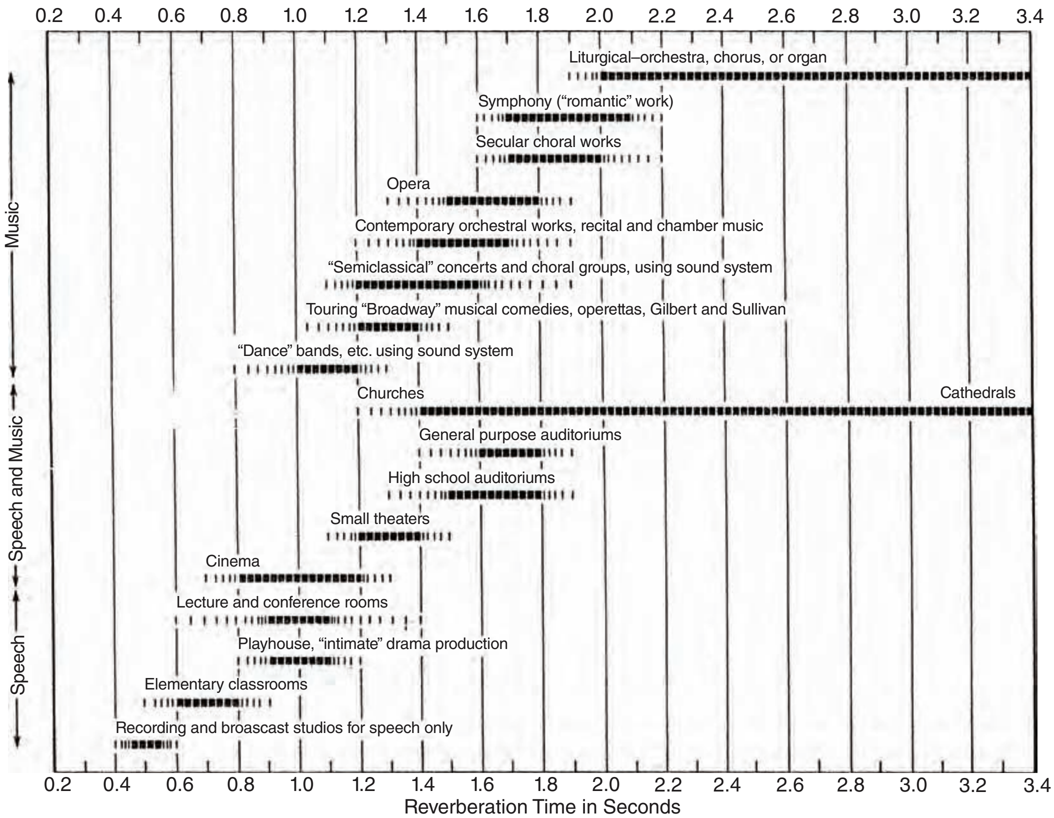


Fig. 23.16 *Optimum reverberation times at midfrequencies (500–1000 Hz) for various types of facilities. The wide range shown reflects the effects of room proportions, shape, and volume on the optimum T_R, as well as differences of opinion among designers.*

time, and ray diagramming, as well as juggling of materials, dimensions, and wall angles. Simulation techniques and acoustic models are also often employed.

Recent research and simulation studies of concert and recital halls have demonstrated that the sensation of fullness of music, or what is today referred to as *sound envelopment*, is enhanced by lateral reflections that reinforce the direct signal. It has also been found that the subjective judgment of reverberance is more strongly affected by *early decay time* (the time required for a 10-dB decrease in signal strength) than by the conventional 60-dB decay time. Finally, crispness or clarity of the music (particularly important in recital halls and for chamber music) depends upon reflections arriving within 40 to 70 ms. All of these factors are considered both in the original design and in the often lengthy "tuning" process of a space intended for music performance. Most modern design solutions also use movable reflector panels and other active variables. After construction is completed, extensive tests are conducted and field adjustments are made.

23.13 SOUND PATHS

Ideally, every listener in a lecture hall, theater, or concert hall should hear the speaker or performer with the same degree of loudness and clarity. Since this is obviously impossible by direct-path sound, the essential design task is to devise methods for reinforcing desirable reflections and minimizing and controlling undesirable ones. Normally only the first reflection is considered in ray diagramming (discussed in the next section) since it is strongest. Second and subsequent reflections are usually

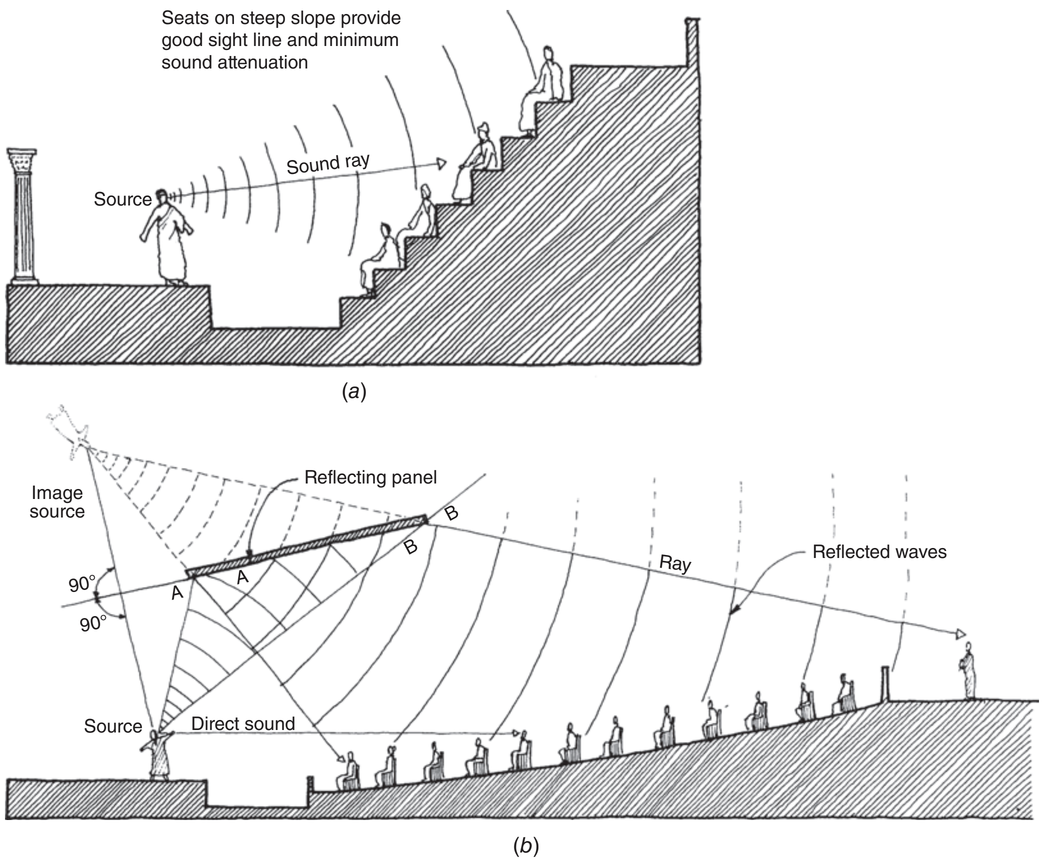


Fig. 23.17 *Use of an angled reflector panel (b) creates an image source that stands in approximately the same relation to the audience as does the performer in the classic Greek theater (a).*

attenuated to the point that they need not be considered except for the special situations of flutter, echoes, and standing waves, discussed in the following sections.

(a) Specular Reflection

Specular reflection occurs when sound reflects off a hard, polished surface. This characteristic can be used to good advantage to create an effective image source. In ancient Greek and Roman theaters, seats were arranged on a steep conical surface around the performers. The virtue of this arrangement (Fig. 23.17*a*) is that the sound energy travels to each location with minimal attenuation. The same effect can be accomplished by placing the sound source above the seats. This is not practical physically, but it can be accomplished effectively by the use of a reflecting panel (Fig. 23.17*b*). The panel dimension must be at least one wavelength at the lowest frequency under consideration. Figure 23.18 is a chart for converting from frequency to wavelength in feet and meters.

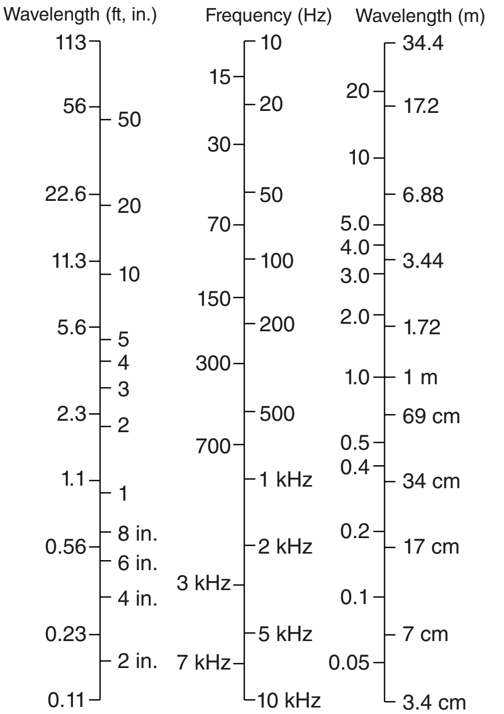


Fig. 23.18 *Nomograph for determining wavelength in feet or meters, given frequency in hertz, or vice versa. Speed of sound is taken as 1128 ft/s (344 m/s). To use it, hold a straightedge horizontally across the nomograph and read the figures directly.*

(b) Echoes

As explained in Section 23.11, a clear echo is caused when reflected sound *at sufficient intensity* reaches a listener more than 50 ms after he or she has heard the direct sound. (Some authorities place this figure as high as 80 ms.) Echoes, even if not distinctly discernible, are undesirable. They make speech less intelligible and make music sound "mushy." The relative undesirability depends upon the time delay and loudness relative to the direct sound, which, in turn, are dependent upon the size, position, shape, and absorption of the reflecting surface.

Typical echo-producing surfaces in an auditorium are the back wall and the ceiling above the proscenium. Figure 23.19 shows these problems and suggests remedies. Note that the energy that produced the echoes can be redirected to places where it becomes useful reinforcement. If echo control by absorption alone were used on the ceiling and back wall, that energy would be wasted. The rear wall, since its area cannot be reduced too far, may have to be made more sound-absorptive to reduce the loudness of the reflected sound.

(c) Flutter

A flutter, perceived as a buzzing or clicking sound, comprises repeated echoes traversing back and forth between two nonabsorbing parallel (flat or concave) surfaces. Flutters often occur between shallow domes and hard, flat floors. The remedy for a flutter is either to change the shape of the reflectors or their parallel relationship, or to add absorption. The solution chosen will depend upon reverberation requirements, cost, and aesthetics.

(d) Diffusion

This is the converse of focusing and occurs primarily when sound is reflected from convex surfaces. A degree of diffusion is also provided by flat horizontal and inclined reflectors (Fig. 23.20). In a diffuse sound field, the sound level remains relatively constant throughout the space, an extremely desirable property for musical performances.

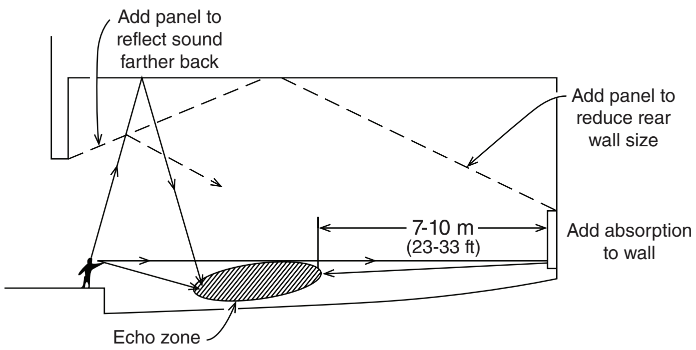


Fig. 23.19 *Auditorium section showing the causes and remedies for two typical echoes.*

(e) Focusing

Concave domes, vaults, or walls will focus reflected sound into certain areas of rooms. This has several disadvantages. For example, it will deprive some listeners of useful sound reflections and cause hot spots at other audience positions (Fig. 23.21*a*).

(f) Creep

This describes the reflection of sound along a curved surface from a source near the surface. Although the sound can be heard at points along the surface, it is inaudible away from the surface. Creep is illustrated in Fig. 23.21*b.*

(g) Standing Waves

Standing waves and flutter are very similar in principle and cause but are heard quite differently. When an impulse (such as a hand clap) is the energy source, a flutter will occur between two highly reflective parallel walls. It is perceived as a slowly decaying buzz. When a steady, pure tone is the source, a standing wave will occur, but only when the parallel walls are spaced apart at some integral multiple of a half-wavelength.

When parallel walls are exactly one-half wavelength apart, the tone will sound very loud near the walls and very quiet halfway between them. This is because at the center, the reflected waves traveling in one direction are exactly one-half wavelength away from those traveling in the other direction, and are thus equal *but opposite* in pressure, which results in total cancellation. In other rooms, standing waves are noted as points of quiet and loudness in the room. Standing waves are important only in rooms that are small with respect to the wavelengths generated (smallest room dimension <30 ft [< 9 m] for music or <15 ft [<4.5 m] for speech).

Another effect of standing waves, called *resonance*, is the accentuation of a particular frequency that will cause a standing wave. Thus, if one speaks (or plays a musical instrument) while standing near a wall of a room about 8 ft × 8 ft (2.4 m × 2.4 m) in size, one will notice an abnormal and sometimes unpleasant loudness in the sound at about 280 Hz.

Similarly, when a musician plays a scale, one note may seem far louder than the adjacent ones, and listeners in one section of the room may hear a

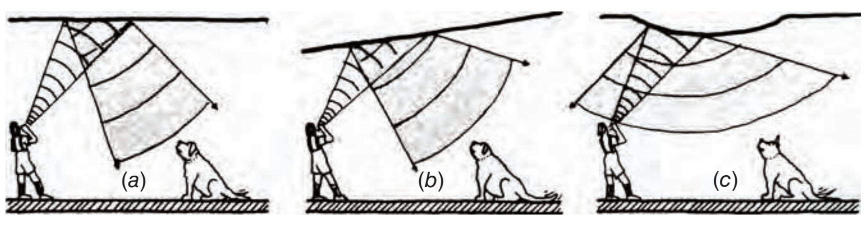


Fig. 23.20 *Sound diffusion can be created with reflectors of different shapes, including horizontal flat (a), inclined flat (b), and convex (c) reflectors. Diffusion improves from (a) to (c).*

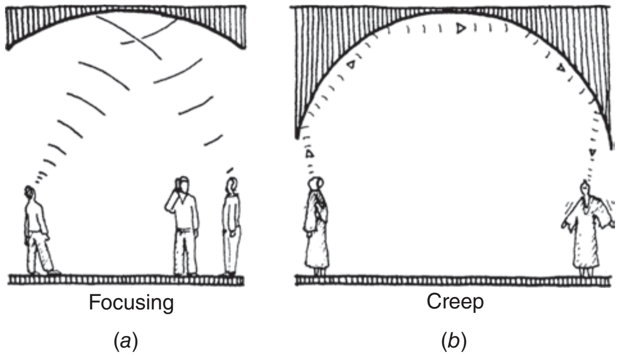


Fig. 23.21 Two undesirable phenomena in room acoustics.

quality of sound different from that heard by those in other sections. This effect *must* be avoided for music performance but is merely an annoyance in rooms designed for speech use. This is one of the reasons that one finds music rehearsal rooms, broadcast studios, and the like with nonparallel walls and undulating ceilings. These irregularities prevent most of the undesirable effects described. However, since rooms with nonparallel walls and undulating ceilings are unacceptable for most applications, and since standing waves and other resonant phenomena are related to room geometry, it is possible to calculate room proportions with conventional geometries that will minimize these effects. Figure 23.22 shows such room proportions, which are applicable to the bass frequencies (i.e., below 100 Hz) that are the problematic frequencies. At higher frequencies (and in large rooms) standing waves may be common, but the overall effect is much less disturbing and frequently hardly noticeable.

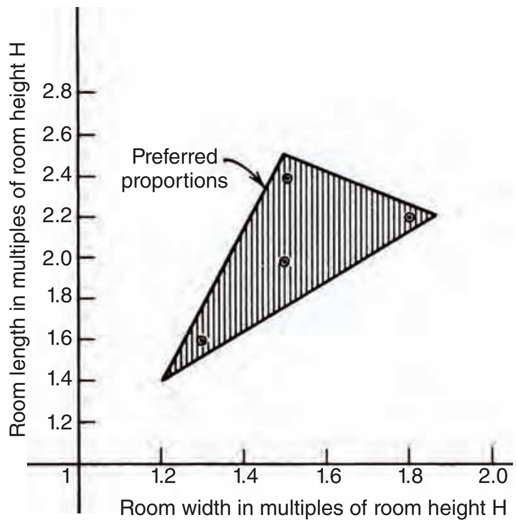


Fig. 23.22 The triangular figure contains the room proportions recommended for avoidance of disturbing low-frequency acoustic phenomena such as flutter, standing waves, and resonances, particularly at frequencies below 100 Hz. The points shown at the three apexes were averaged to obtain the center point with a proportion of 2H:1.5H:H.

23.14 RAY DIAGRAMS

Ray diagramming is a design procedure for analyzing the reflected sound distribution throughout a hall, using the first reflection only. Figure 23.23 shows a ray diagram. The rays are drawn normal (perpendicular) to the spherically propagating sound waves. Specular reflection is assumed—that is, at reflecting panels, the angles of the incident and reflected rays are always equal. Thus, in addition to direct sound, each listener is receiving reflected sound energy. It is as though there were additional sound sources, the real one and numerous image sources. Figure 23.23 shows the application of a ray diagram to the design of a lecture hall. In Fig. 23.23*a*, the stage height and seating slope are arranged to provide good sight lines, and the ceiling height is established by reverberation requirements, aesthetics, cost, and so on. It can be seen that less than half of the ceiling is providing useful reflection. Dividing the ceiling into two panels (Fig. 23.23*b*) allows people in the rear of the room to perceive the direct source plus two image sources—increasing the useful reflecting area by 50%. In Fig. 23.23*c*, the shape has been further refined to include a lighting slot and a loudspeaker grille.

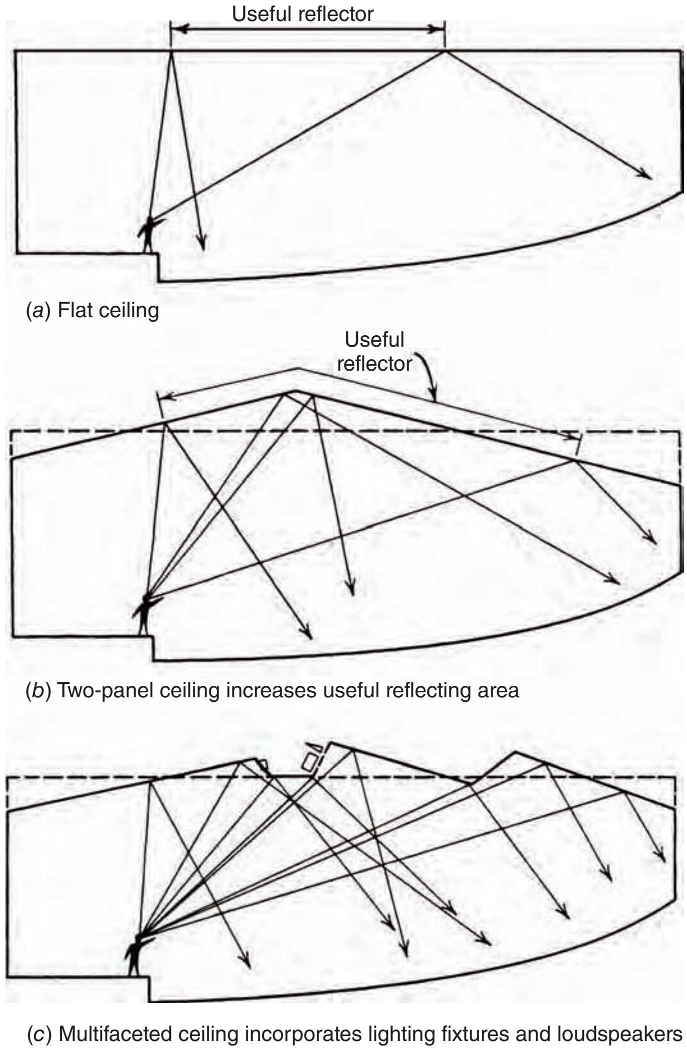


Fig. 23.23 *Section through a typical lecture room showing the use of ray diagrams.*

As mentioned previously, the sensation of musical envelopment that is so satisfying to a listener, particularly when dealing with large groups playing symphonic music, is due in large measure to reflections received from the side (lateral reflections). This being so, ray diagramming, which was originally performed on room *sections* to determine ceiling shapes and the proper placement of ceiling-hung reflector panels, is now done in *plan* as well. This is particularly important in fan-shaped auditoriums, where a canted wall does not provide useful lateral reflections. The solution to this problem is to build a sawtooth wall or to use reflector panels along the wall that will provide the desired lateral reflection. Nonhorizontal ceiling reflector panels can also provide a measure of lateral reflection, particularly in balconies.

Although they are a useful design tool, ray diagrams have certain restrictions. Design solutions always will require compromise between ray diagram results for various speaking positions on a stage. Thus, a paraboloid may be a perfect shape for one source position but a very poor shape for other positions.

23.15 AUDITORIUM DESIGN

Auditorium is a general term used to describe a space where people sit and listen to speech or music. Acoustical design of an auditorium includes room acoustics, noise control, and sound system design. Noise control is covered in Chapter 24, and sound systems are discussed in Sections 23.16 through 23.18. If the program for the auditorium includes activities that require different acoustical environments (as is frequently the case), then it must be decided early whether the acoustics will be a compromise between the program extremes or adjustable for various activities. Acoustical environments can be altered by changing the space volume, moving reflecting surfaces, and adding or subtracting sound-absorbing treatment. Figure 23.24 illustrates several examples of acoustical adjustability.

Factors that influence acoustical design include: audience size, range of performance activities, and sophistication of the potential audience and performers. A small school auditorium (Fig. 23.25a) and a professional theater (Fig. 23.25b) will have widely divergent demands from both audiences and performers. The audience size determines the basic floor area of an auditorium, assuming no balconies. Once this area has been fixed, the volume of the room is developed according to reverberation requirements of the space.

Figure 23.26 shows a typical auditorium in plan and section. The shape of the wall and ceiling surfaces is developed to provide proper distribution of sound and eliminate focusing or echoes. Essential characteristics of the design include:

1. Ceiling and side walls at the front of the auditorium distribute sound to the audience. These surfaces must be close enough to the performers to minimize time delays between direct sound and reflected sound.
2. Ceiling and side walls provide diffusion.

Acoustics must be considered in the selection of materials used in an auditorium. All auditoriums use both sound-reflecting and sound-absorbing materials. Since the largest area of sound-absorbing material in any auditorium is the audience, the difference in acoustical characteristics that occurs without an audience may be minimized by using fully upholstered seating.

Chairs with fully upholstered seats and backs, covered in an open-weave material, will have absorption characteristics approximating those of an audience. Using the auditorium in Fig. 23.26 as an example, the reverberation

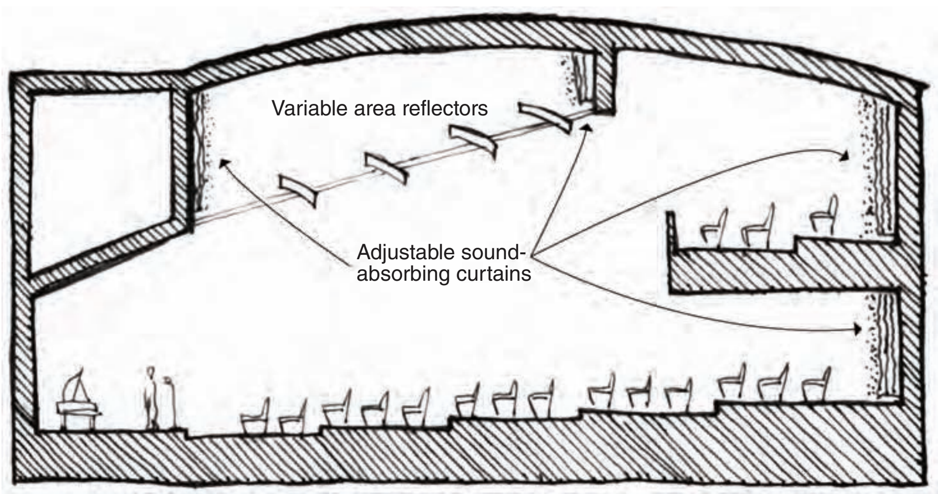
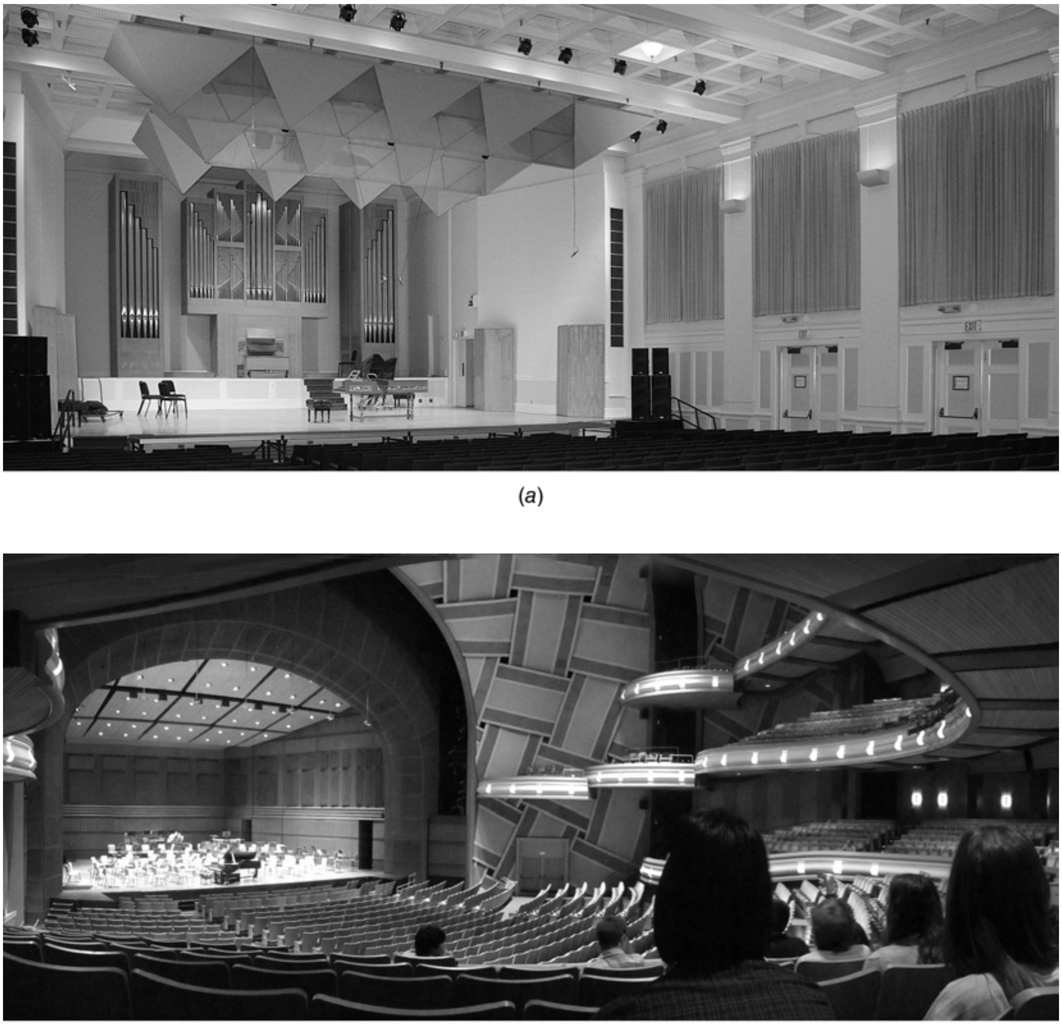


Fig. 23.24 *Adjustable acoustic elements in an auditorium. (Redrawn by Zeta Fernando.)*

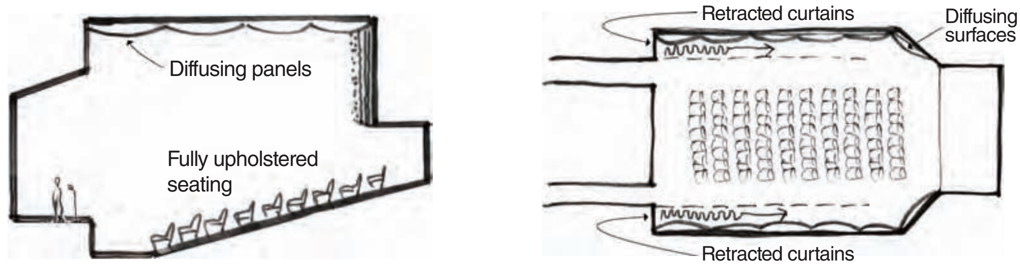


(*a*)

(*b*)

Fig. 23.25 *(a) An institutional, shoebox-style auditorium. University of Oregon's Beall Hall, designed by Ellis F. Lawrence, is a simplified rendition of the Boston Symphony Hall. The combination of pyramidal sound diffusers, a coffered ceiling, and sound-absorptive wall curtains provides optimal sound conditions for performances within the School of Music. (b) Auditorium with a variety of sound-absorbing and sound-reflecting materials. The Hult Center's Silva Concert Hall in Eugene, OR, features convex wall and ceiling panels, diffusing panels, and sound-absorptive upholstery to reduce reverberation and increase sound clarity. (a) © Karen Tse; used with permission; (b) © Tyler Mavichien; used with permission.*

characteristics of an auditorium with various materials may be examined—as shown in the following analysis. In one configuration, the room use is assumed to be for music performances; the only sound absorption is that provided by the audience and seating. In the second configuration, absorptive curtains are installed along the rear wall and a portion of the side wall; this configuration might be used for lectures in a room that is adjustable between speech and music configurations. A third configuration might use permanent sound-absorbing treatment installed on the ceiling and rear and side walls; because of its low reverberation time, this configuration would



(a) (b)

Fig. 23.26 *Auditorium analysis illustrating the use of surface treatments for control of reflections and reverberation.*

Simplified Calculations of Midfrequency (500 and 1000 Hz) Average Reverberation Time

$$\text{Reverberation time } (T_R) \text{ in seconds} = \frac{0.05 \times \text{volume in ft}^3}{\text{total absorption in sabins}}$$

$$\left[\text{Reverberation time } (T_R) \text{ in seconds} = \frac{0.16 \times \text{volume in m}^3}{\text{total absorption in sabins}}\right]$$

room volume = 155,500 ft^3 (4404 m^3) area in ft^2 (m^2) absorption in ft^2 (m^2 sabins)

more reverberant condition; with curtains retracted

	Area	***Alpha***	***Absorption***
Seating and stage; with audience and performers	3323 (309)	0.92	3060 (284)
Wall area; concrete block	8000 (743)	0.2	1600 (149)
Lower rear wall; permanent sound-absorbing treatment	450 (42)	0.88	396 (37)
Total absorption			5056 (470)
More reverberant condition			$\frac{0.05 \times 155{,}500}{5056}$ = 1.5 sec $\frac{[0.16 \times 4404]}{470}$ = 1.5 sec

less reverberant condition; with curtains exposed

	Area	***Alpha***	***Absorption***
Seating and stage; with audience and performers	3323 (309)	0.92	3060 284
Wall area; concrete block, balance covered by curtains	3600 (334)	0.2	720 (67)
Curtains	4400 (409)	0.45	1970 (184)
Lower rear wall; permanent sound-absorbing treatment	450 (42)	0.88	396 (37)
Total absorption			6146 (572)
Less reverberant condition			$\frac{0.05 \times 155{,}500}{6146}$ = 1.2 sec $\frac{[0.16 \times 4404]}{572}$ = 1.2 sec

be appropriate only for movies and lectures, not for music activities.

These simple examples indicate the effect of changes in the amount of absorption on the characteristics of a room. Adjustable treatments permit the characteristics of the room to be modified to any point between the extremes to meet the acoustic program requirements of a multipurpose hall.

Existing spaces may require remedial treatment to eliminate unwanted phenomena such as focusing and echoes, as shown in Fig. 23.27. In the first example, the surface of the dome was covered with sound-absorbing material to eliminate focusing; in the second, sound-absorbing treatment was applied to a curved rear wall to eliminate an echo.

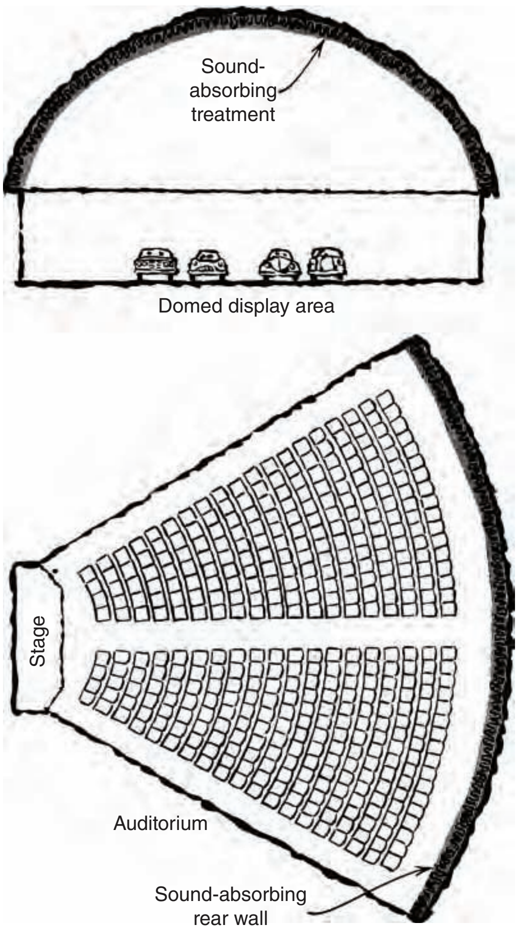


Fig. 23.27 *Sound-absorbing treatment used to eliminate focusing from the dome and the curved auditorium wall.*

Such treatment will also affect the reverberation characteristics.

SOUND REINFORCEMENT SYSTEMS

23.16 OBJECTIVES AND CRITERIA

The purpose of a sound reinforcement system is just what the name indicates—to reinforce sound levels that would otherwise be inadequate. An ideal sound-reinforcing system will give the listener the same loudness, quality, directivity, and intelligibility as would result if the source of sound were immediately adjacent to the listener—a distance of 2 to 3 ft (0.6 to 0.9 m) for speech, and farther for music (depending upon the type and number of instruments). In this ideal system, there are several factors that should remain constant—loudness, intelligibility, quality, and so on. Of these factors, loudness and intelligibility have previously been discussed. By *quality* we mean that the frequency response should be linear so that reproduced sound bears the same relation to its frequency components as the original sound. (Quality is then field-adjusted by voicing or equalization, as discussed in Section 23.17.)

Directivity is the characteristic whereby the sound appears to be coming from the originating source, that is, the loudspeakers should be directionally "invisible," and the listener must have the impression of actually hearing the source. It should be emphasized that sound systems cannot correct a poor acoustic design completely, although they can improve a bad situation.

Generally, sound systems will be required in spaces larger than 50,000 ft^3 (≈1400 m^3). In terms of occupancy, this volume translates into 550 persons in lecture rooms (15-ft [4.6-m] average ceiling height and 6 ft^2 [0.6 m^2] per person) and 325 persons in theaters (20-ft [6.1-m] average ceiling height and 7.5 ft^2 [0.7 m^2] per person). In such a room, a normal speaking voice can maintain a sound pressure level of only 55 to 60 dB, depending upon room design, voice strength, and frequency. With background noise at NC 30 (see Table 24.8), a speaker will be heard; at higher background noise levels, intelligibility will suffer.

23.17 COMPONENTS AND SPECIFICATIONS

All sound systems consist of three basic elements: input devices, amplifier(s), and loudspeaker systems.

(a) Input

Input usually means a microphone, a source of commercial broadcast material of various types, and a means of reproducing recorded material in all common commercial formats. Connections to local computers and computer networks are available in sophisticated systems.

(b) Amplifier and Controls

Amplifiers must be rated to deliver sufficient power to produce intensity levels of 80 dB for speech, 95 dB for light music, and 105 dB for symphonic music. This assumes a *maximum* background noise level of 60 dBA. Thus, 80-dB speech intensity will be 20 dB higher—or four times as loud as the noise level. If the noise level is *known* to be below 60 dBA maximum, amplifier and loudspeaker power ratings can be reduced accordingly. The amplifier should carry technical specifications for signal-to-noise ratio, linearity, and distortion. Exact values depend upon the application and are left to the acoustics specialist or sound engineer to supply.

In addition to the usual volume, tone mixing, and input/output selector controls, the amplifier *must* contain special equalization controls for signal shaping. These are highly critical filter networks that, by selective amplification and attenuation of portions of the overall audio frequency spectrum, *voice* or *equalize* a system after installation. Equalization is the *sine qua non* of a good sound system; without it, the system will howl, sound rough, give insufficient and poorly distributed gain and sound level, and generally produce bad sound. Essentially, voicing tailors the system to the acoustic properties of the space. A system not equipped for equalization is not a professional system, and results will verify it. Furthermore, the specification must provide for the services of a competent sound engineer to perform the equalization after construction and system installation are complete.

Another control frequently required in theater systems is a delay mechanism or circuit that can introduce a time delay into a signal being fed to a loudspeaker. Figure 23.28 shows a sound system that covers a majority of an auditorium from a central loudspeaker cluster. The under-balcony seating areas are hidden from the central cluster and receive reinforced sound from distributed loudspeakers in the under-balcony soffit. To provide directional realism, the signal to the under-balcony loudspeakers must be delayed to allow the weaker signal from the central speakers to arrive first. Delay is necessary because electrical signals travel at the

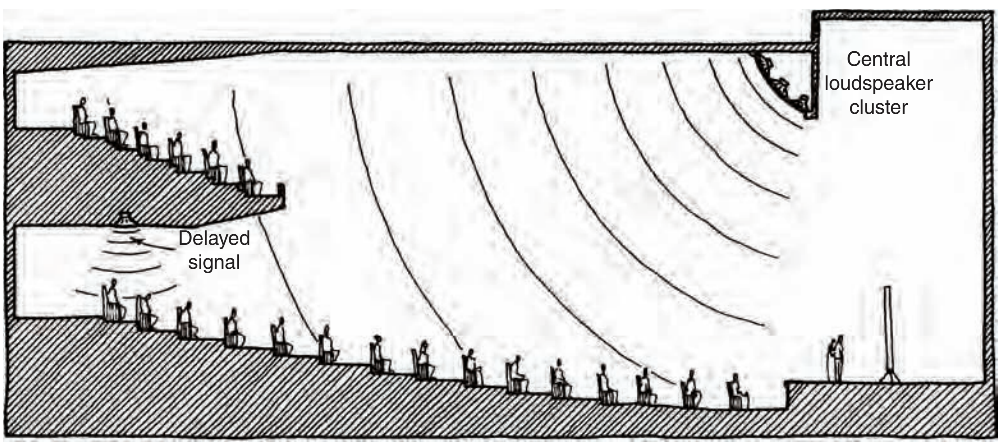


Fig. 23.28 *Loudspeaker system using a delayed signal to the under-balcony area.*

speed of light, whereas sound is much slower (one-millionth of light speed, approximately). With this arrangement, sound will seem to come from the source, and the directivity so necessary to realism is maintained.

(c) Loudspeakers

These are the heart of any sound system and must be of the same high quality as the remainder of the system. Indeed, scrimping on system costs will show up much more quickly in loudspeaker performance than in any other component. Selection of speakers is a complex technical task beyond the scope of our discussion. Nevertheless, a few general remarks are in order. The best systems with traditional components use central-speaker arrays consisting of high-quality, sectional (multicell), directional, high-frequency horns and large-cone woofers. These assemblies are frequently very large, and the architect should be aware of the dimensions that must be accommodated. Smaller units with folded horns can be used, at a sacrifice in low-frequency response. If only speech is to be reproduced, these units will perform adequately. Distributed systems use small (4- to 12-in. [100- to 305-mm]) diameter low-level speakers, ceiling-mounted and firing directly down.

Recent developments in loudspeaker design have produced units much smaller than those previously required for high-power, high-quality, low-frequency sound reproduction. Here again, the considerations are highly technical, and speakers should be supplied under a performance

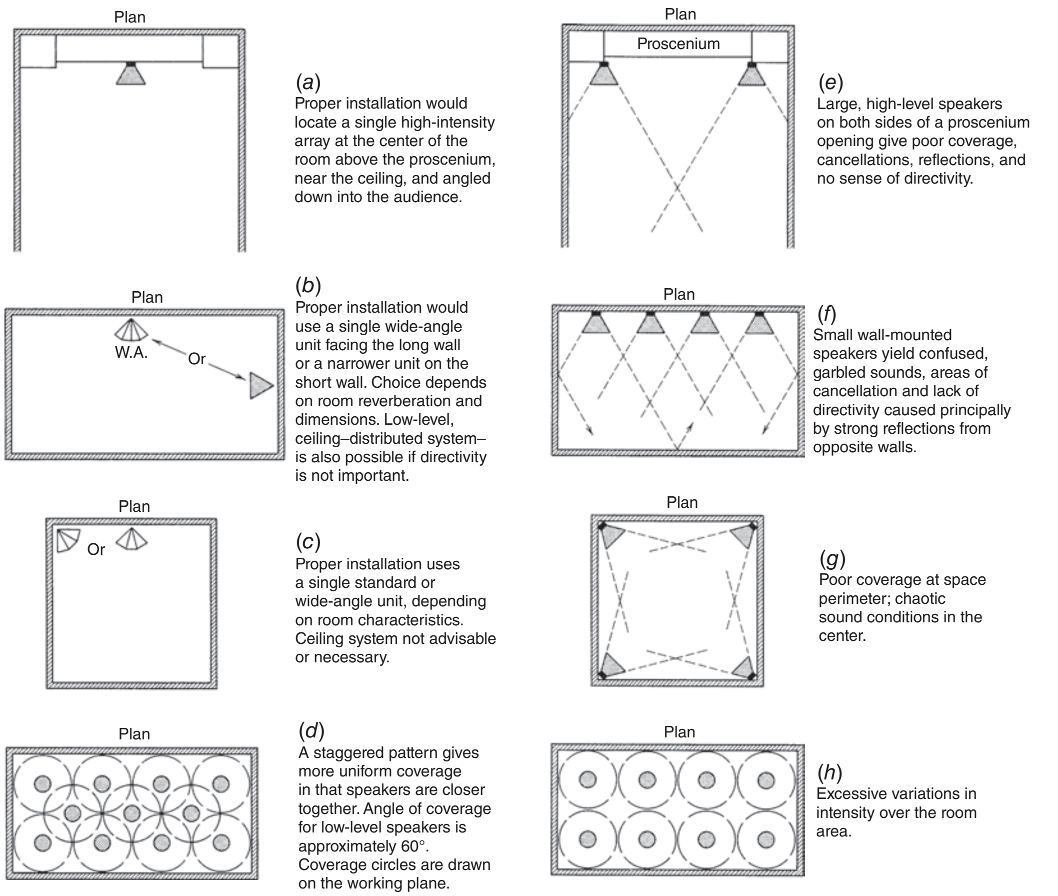


Fig. 23.29 *Good speaker layouts (a–d) and poor layouts (e–h). Wide-angle speakers are available to fit most needs. Ceiling speakers give effective coverage on a 60° cone. The working plane is taken to be 4 ft (1.2 m) above the finished floor (AFF) for a seated audience and 6 ft (1.8 m) AFF for standing listeners.*

specification that guarantees user satisfaction subject to specified test procedures.

23.18 LOUDSPEAKER CONSIDERATIONS

Loudspeaker system design and placement must be coordinated with the architectural design. The two principal types of loudspeaker systems are central and distributed. The loudspeakers in a conventional central system are a carefully designed array of directional high-frequency units, combined with less directional low-frequency units placed above and slightly in front of the primary speaking position. In most theaters, this location is just above the proscenium on the centerline of the room. Located in this position, the system provides directional realism and is simple in its design.

A distributed loudspeaker system consists of a series of low-level loudspeakers located overhead throughout the space. Each loudspeaker covers a small area, in a manner similar to downlights. This type of system is used in low-ceiling areas where a central loudspeaker cluster cannot provide proper coverage. It also can be used for public address functions where directional realism is not essential, in spaces such as exhibition areas, airline terminals, and offices. In public areas such as transportation terminals, where the absence of absorptive material makes such spaces highly reverberant, particular care must be taken in speaker positioning and volume levels. Failure to do so will result in the unfortunately very common condition of extremely loud yet unintelligible speech.

Distributed loudspeaker systems provide flexibility for use in spaces where source and listener locations vary according to the use of the space, since loudspeakers can easily be switched to provide proper coverage. In general, a listening position should receive sound from only one loudspeaker. Systems that cover seating areas with signals from several scattered loudspeakers will increase the loudness of the sound but tend to produce garbled speech. This rule is the principal reason that the arrangements shown in Fig. 23.29*e–h* will guarantee a bad job. The common practice of placing one loudspeaker on either side of a proscenium opening (Fig. 23.28*e*), or rows of speakers on one or both sides of a room (Fig. 23.29*f*), therefore, is particularly to be deplored.

Location and design of the sound system control position can create problems for the architect. The sound system operator must be within the coverage pattern of the loudspeakers. For proper operation, he or she should be able to hear the sound as it is heard by the audience. Some current auditorium designs locate sound system controls within the audience seating area. Other designs place a control room with a completely open wall or a large window at the rear of the auditorium. Monitor loudspeakers and earphones are inadequate substitutes for actual listening within the auditorium. In churches, the control equipment can usually be located at the rear of the congregation area.

References and Resources

ASTM. 2000. Standard E795-00, *Standard Practices for Mounting Test Specimens During Sound Absorption Tests*. ASTM International.West Conshohocken, PA.

Beranek, L. L. 1988. *Noise and Vibration Control,* revised ed. Institute of Noise Control Engineering. Washington, DC.

Bruel, P. V. 1951. *Sound Insulation and Room Acoustics*. Chapman and Hall. London.

Magrab, E. B. 1975. *Environmental Noise Control*. John Wiley & Sons. Hoboken, NJ.

CHAPTER 24

Building Noise Control

NOISE REDUCTION

NOISE CONTROL IN BUILDINGS INVOLVES three key concepts:

1. Reduction of noise generation at the source by proper selection and installation of equipment
2. Reduction of noise transmission from point to point (along the transmission path) by proper selection of construction materials and appropriate construction techniques
3. Reduction of noise at the receiver through acoustical treatment of the relevant spaces to meet the noise criteria developed in Chapter 22

Speech privacy is achieved by manipulation of all of the foregoing plus the use of masking noise where necessary.

Noise reduction is essentially the science of converting acoustical energy into another, less disturbing form of energy—heat. Since the amounts of energy involved are minute—130 dB corresponds to 1/1000 of a watt, or 0.003 Btu/h—the heat produced is completely negligible. This energy conversion is accomplished by absorption of sound energy by the room contents and surface coverings and also by the structure itself. The former controls noise levels *within* a space and the latter noise transmission between spaces. The reasons for this will become clear as our discussion proceeds.

ABSORPTION

24.1 THE ROLE OF ABSORPTION

Absorptive noise control treatment of a room will affect the reverberant noise level *within* that room but will have a minimal effect on the noise level in adjoining spaces. Refer to Fig. 24.1 for a graphic presentation of this fundamental fact. The best that can be accomplished with acoustic room treatment is elimination of the reverberant field, that is, making the intensity at the room boundaries what it would have been in free space, as in Fig. 24.1*d*. (Even this is extremely difficult; the actual field at the wall would be above 72 dB, except in a completely anechoic chamber.) Adding further wall (or other) acoustic absorbent (as in Fig. 24.1*e*) does nothing in the room itself and has a minimal effect on the overall transmission loss, since the transmission loss in the acoustic material itself is very low, as can be seen in Fig. 23.1.

The subject of acoustic energy absorption and absorptive materials, and their effect on room acoustics (including noise reduction) is treated extensively in Sections 23.1 through 23.10 for porous absorptive materials. Two other types of absorptive material are in use, although much less commonly: panel resonators and cavity resonators.

(*a*) TV set in free space produces 75-dB sound level, which drops 6 dB for each doubling of distance. Attenuation by inverse square law.

(*b*) TV still produces 75 dB. In the free field, sound drops to 72 dB but builds up to 74 dB at the wall due to reverberant field reinforcement. Wall attenuation is 30 dB. Sound on other side of the wall is 74 – 30 = 44 dB.

(*c*) Acoustic tile ceiling acts to reduce room reverberant field. Free field is extended. Level at wall is 73 dB. Level in second space is 73 – 30 = 43 dB.

(*d*) The room is acoustically treated, effectively eliminating reverberant field. Room is "dead". Level on second side of wall is 72 dB less acoustic tile loss, less wall loss (that is, 72 – 2 – 30 = 40 dB).

(*e*) Add another 2¼ in. of acoustic wall treatment. Room is "dead". Level at wall 72 dB. Level in second space = 72 – 4 – 30 = 38 dB.

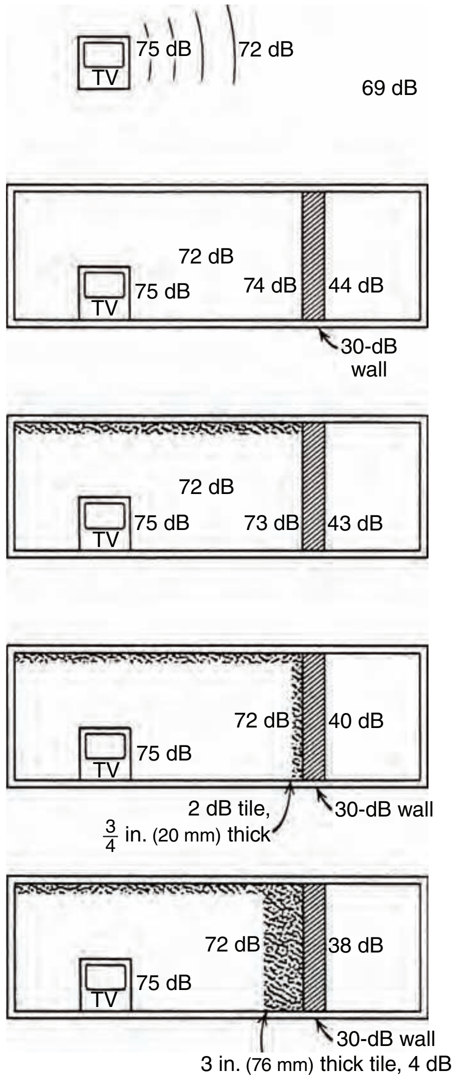


Fig. 24.1 *Graphic description of the effect of porous absorptive material on sound fields and sound pressure level (SPL) in adjoining spaces.*

24.2 PANEL AND CAVITY RESONATORS

Panel resonators are built with a membrane such as thin plywood or linoleum in front of a sealed air space generally containing absorbent material. The panel is set in motion by the alternating pressure of the impinging sound wave. The sound energy is converted into heat through internal viscous damping. Panel resonators are used where efficient low-frequency absorption is required and middle- and high-frequency absorption is unwanted or provided by another treatment (Fig. 24.2). Panel resonators are often used in recording studios.

A *volume* or *cavity resonator* (Helmholtz resonator) is an air cavity within a massive enclosure connected to the surroundings by a narrow neck opening. The impinging sound causes the air in the neck to vibrate, and the air mass behind causes the entire construction to resonate at a

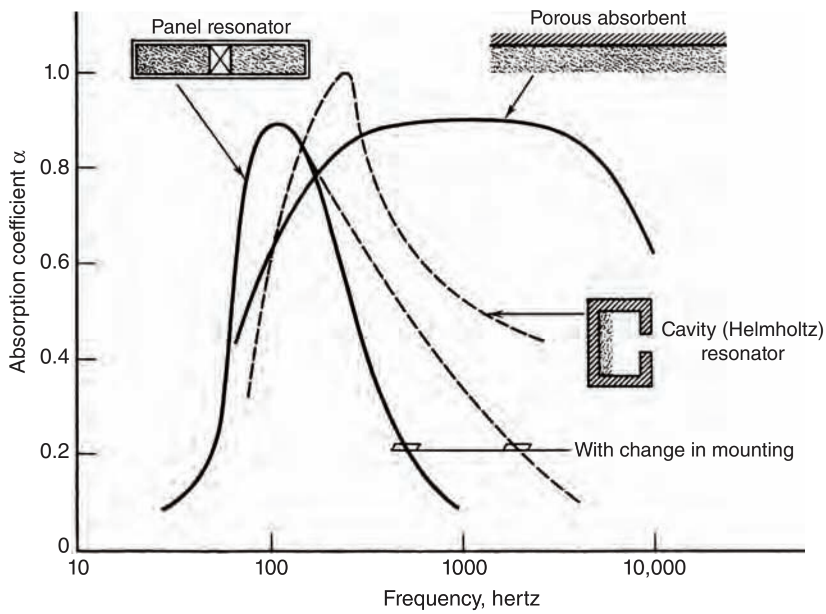


Fig. 24.2 *Typical absorption curves for the three major types of sound absorbers. The absorption characteristic of each type can be changed by varying the design, as discussed in the text.*

particular frequency. At that frequency absorption approaches 100%, but drops fairly sharply above and below this frequency (see Fig. 24.2). Adjusting the neck opening and cavity dimensions allows a unit to be tuned to resonate at different frequencies. This makes it extremely useful when a major single frequency is present, as with 120-Hz transformer hum. Concrete blocks can be used as resonators by tuning their cavities. Their absorption characteristic over the entire frequency band is improved by adding absorptive material in the cavities. Fibrous filler can be used in the block to increase high-frequency absorption. The blocks also serve as standard concrete construction blocks. See Fig. 24.3 for typical block details and Fig. 24.4 for a common application.

24.3 ACOUSTICALLY TRANSPARENT SURFACES

The soft, porous material of which acoustic absorbents are constructed may be covered with perforated metal or other materials to provide physical protection and act as stiffeners. These coverings are generally acoustically transparent except at higher frequencies. The frequency at which a noticeable reduction in absorption occurs for a perforated metal cover with circular holes can be estimated as

$$f = \frac{40p}{d} \tag{24.1}$$

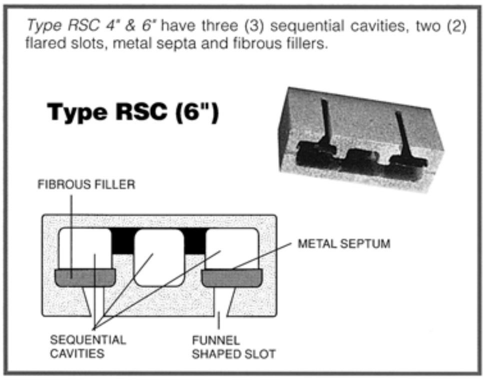
where

f = frequency, Hz
p = percentage of open area
d = diameter of holes, in.

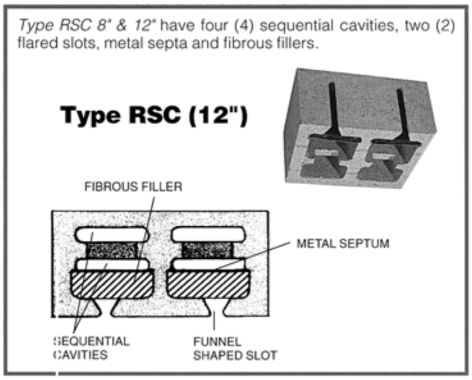
Thus, for ¼-in. holes and 60% open area, which is a typical commercial material,

$$f = \frac{40(60)}{0.25} = 9600\,\text{Hz}$$

which is very high and generally not of major concern. It is always preferable, given a fixed percentage of open area, to use covers with small holes rather than large ones since, as seen from the formula, this raises the frequency at which absorption drops. It is also desirable to stagger the holes, because this improves absorption. An open-weave



(a)



(b)

Sound Absorption Coefficients — Type RSC

Size	Type	Surface	Exposed Slots/ Cavities	FREQUENCY – Hertz 125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	NRC
6"	RSC	PAINTED	2/3	.48	.70	.93	1.14	1.05	.97	.91	.84	.75	.76	.77	.70	.67	.68	.56	.51	.59	**.85**
8"	RSC	PAINTED	2/4	.48	.85	1.17	.99	.90	.88	.98	.79	.62	.58	.60	.61	.70	.69	.70	.64	.51	**.80**
12"	RSC	PAINTED	2/4	.57	*	*	.76	*	*	1.09	*	*	.94	*	*	.54	*	*	.59	*	**.85**

(c)

Fig. 24.3 *Details of a Helmholtz resonator design using concrete blocks, with tuned block cavities as the resonating chambers. (a) A 6-in. (150-mm) block with three sequential cavities tuned with a metal divider (septum). (b) A 12-in. (305-mm) block with four cavities and added absorptive filler. (c) Sound absorption coefficients. (Courtesy of The Proudfoot Co., Inc.)*

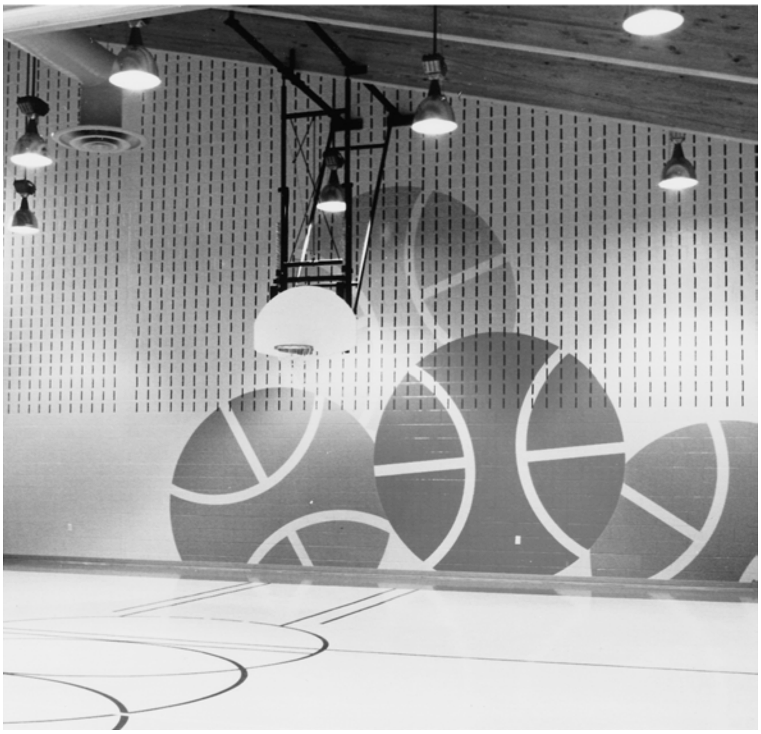


Fig. 24.4 *Application of concrete block resonators in a school gymnasium. (Courtesy of The Proudfoot Co., Inc.)*

fabric is almost completely transparent to sound and is often used as a decorative cover on absorbent wall coverings.

24.4 ABSORPTION RECOMMENDATIONS

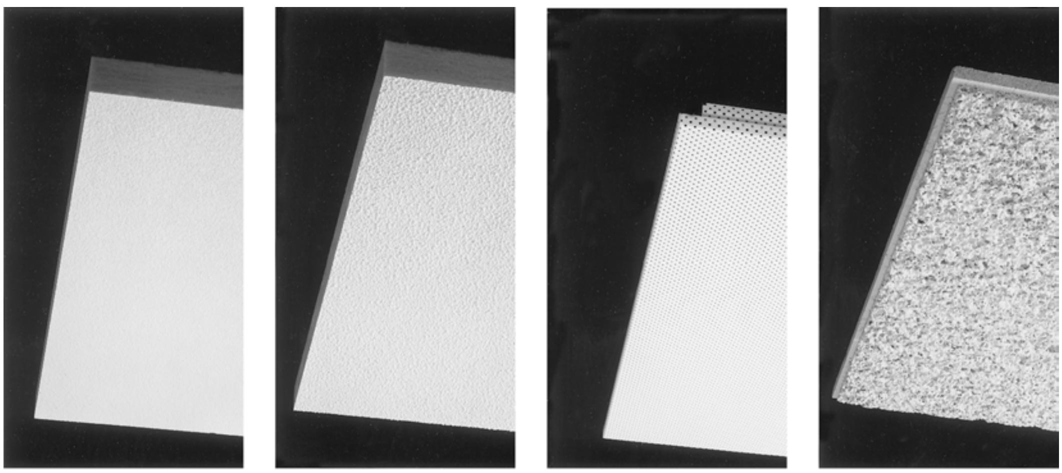
To summarize, absorption techniques are useful and effective:

1. To change room reverberation characteristics
2. In spaces with distributed noise sources such as offices, schools, restaurants, and machine shops
3. In spaces with hard surfaces and little absorptive content
4. Where listeners are in the reverberant field (no amount of absorptive material can reduce intensity levels in the free field)

Concentrated noise sources are better handled by individual equipment enclosures than by room treatment, since enclosures reduce the amount of sound emitted into a room, which room surface treatment cannot do. In addition to ceiling tiles and wall panels, acoustic absorbent material can be applied in the form of a sprayed-on finish (acoustic plaster), suspended unit absorbers, carpets, draperies, and the like.

24.5 CHARACTERISTICS OF ABSORPTIVE MATERIALS

1. *Acoustic tile* is available in size multiples of 12 in. (nominal 305 mm), from 12 in. × 12 in. (305 mm × 305 mm) up to 48 in. × 96 in. (1.2 m × 2.4 m), in a huge variety of patterns and finishes, including units with fire ratings. Installation methods include lay-in, nailing to furring strips, and gluing. Tile materials are generally mineral fiber or faced fiberglass, with noise reduction coefficient (NRC) ratings in the range of 0.45 to 0.75 for mineral fiber tiles and up to 0.95 for fiberglass. The latter, which are frequently used in open-office applications, have Articulation Class (AC) ratings of 170 to 210 (see Section 24.20*d*). Tiles for use in high-humidity areas should be certified by the manufacturer for that application (see Fig. 24.5).



(*a*) (*b*) (*c*) (*d*)

Fig. 24.5 *Four of the many types of acoustic ceiling tiles available are illustrated. (a) and (b) are 24 in. × 48 in. × 1.5 in. (600 mm × 1200 mm × 36 mm) fiberglass ceiling tiles with an acoustically transparent plastic humidity shield facing and a foil back for good sound dispersion in the plenum of open-plan offices. (a) Tile has 1.0 NRC, 200 AC (Articulation Class), 0.89 light reflectance, and a thermal R value of 4.0. (b) Tile has similar acoustic and thermal characteristics, but due to its coarser surface, its light reflectance is 0.85. Both tiles are applicable to open-plan offices and are usable with indirect lighting systems. (c) Perforated metal cassette panels are used in lobbies, corridors, entries, outdoor canopies and soffits, and areas with high humidity. They are usable for HVAC system air returns and, when supplied with an acoustic infill (mineral fiber or fiberglass), have good acoustic properties. (d) General-purpose, coarse-textured mineral fiber ceiling tile is rated 0.70 NRC, 25 CAC (Ceiling Attenuation Class), and 0.73 light reflectance. It can be used acoustically in offices, libraries, restaurants, and public spaces. (Photos courtesy of Armstrong World Industries.)*

2. *Perforated metal-faced units* are usually installed in a lay-in suspension ceiling, although nailing to furring strips is possible. Units range in size from 12 in. × 24 in. (305 mm × 610 mm) to 24 in. × 96 in. (0.6 m × 2.4 m)—and larger on special order. The fill material is either wrapped mineral wool or fiberglass, with NRC ratings somewhat lower than those of acoustic tile of the same material. The metal finish is generally baked enamel in a range of colors. The units are applicable to all spaces and have the advantages of easy cleaning, high luminous reflectivity, and incombustibility. With the acoustic backing removed, a perforated unit can be used for air return (Fig. 24.5*c*).

3. *Acoustic panels* (boards) are made of treated wood fibers, bonded with an inorganic cement binder, in sizes ranging from 12 in. × 24 in. (305 mm × 610 mm) to 24 in. × 120 in. (610 mm × 3050 mm), with thicknesses from 1 to 3 in. (25 to 75 mm) and a smooth or "shredded" finish. Panels are used in ceiling suspension systems, or nailed or glued when applied to walls and structural ceilings. Their principal advantage is their high structural strength, which makes them applicable to installations requiring acoustic treatment combined with strength and abuse-resistance. A second advantage is their excellent flame-spread rating. Typical applications include full-span corridor ceilings, long-span direct-attached ceiling finish, wall panels in school gyms and corridors, and the like. NRC ratings range from 0.40 to 0.70. Acoustic panels are usually resistant to humidity, but usage in high-humidity spaces should be confirmed with the product manufacturer. This is particularly true for panels with "reveal" edges (Fig. 24.6).

4. *Acoustic plaster*, a material comprising a plaster-type base into which is introduced fibrous or light aggregate, is useful for application to curved and other nonlinear surfaces, in thicknesses of up to 1.5 in. (38 mm). Its advantages are ease of application and a high fire rating; its disadvantages are its inability to resist even mild abuse and its inapplicability to humid atmospheres. The noise absorption characteristics of acoustic plaster vary widely with composition, thickness, and application technique, and are generally below those of acoustic tile and panels.

Fig. 24.6 *Acoustic panel material made of pressed organic fiber with an inorganic binder can be used as ceiling tile or wall panels. The latter has cloth covering as an outer finish. (Courtesy of Tectum, Inc.)*

5. *Sound blocks*, *baffles*, and *hanging panels* are simply masses of absorptive acoustic material that achieve absorption coefficients in excess of 1.0 by exposing more than a single absorptive surface to the impinging sound. For one product (an 8 ft^2 [0.7 m^2] baffle), absorption coefficients are reported as 0.66 @ 250 Hz, 1.31 @ 500 Hz, and 1.74 @ 1000 Hz. In all cases, because of their prominent appearance, necessitated by their shape, they obtrude into the space and frequently become a major architectural element. This is especially true of hanging baffles (Fig. 24.7).

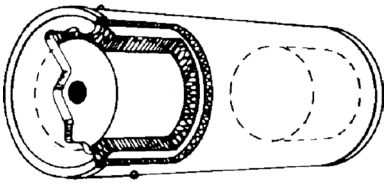
6. *Wall panels* consist of a wood or metal backing on which is mounted a mineral fiber or fiberglass substrate and a fabric covering. NRC coefficients vary from 0.5 for direct-mounted 1-in. mineral fiber substrate to as high as 0.85 for strip-mounted 1.5-in. (38 mm) fiberglass substrate panels. Wall panels are available in widths ranging from 18 to 48 in. (457 to 1220 mm) and lengths of up to 120 in. (3050 mm). Fabric coverings generally carry a fire-spread rating. These panels are frequently used in offices, conference rooms, auditoriums, theaters, teleconferencing centers, and educational facilities (see Fig. 24.8).

Fig. 24.7 *Application of hanging acoustic baffles to reduce reverberation in the high pyramid-shaped volume of a hotel lobby in Hong Kong. (© Alison Kwok; all rights reserved.)*

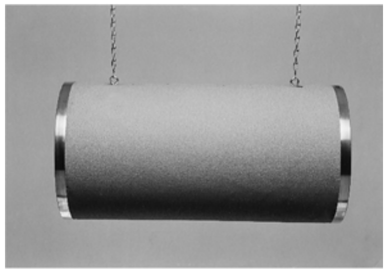
Fig. 24.8 *Acoustic wall panel consists of a rigid backing covered with either mineral fiber or fiberglass and finished with any of a wide selection of fabrics. NRC averages 0.6 for mineral fiber substrate and 0.8 for fiberglass with contact mounting (A mounting), and 0.7 to 0.9 when the panels are mounted on 2-cm (nominal ¾-in.) furring strips (D-20 mounting). The latter mounting is particularly effective in increasing absorption below 500 Hz. (Courtesy of Armstrong World Industries.)*

7. *Resonator sound absorbers* are available in a wide variety of sizes and shapes. Although some designs are available off the shelf, most are tailored to the specific acoustic needs of a project, using one of several standard designs. One fairly common type is shown in Fig. 24.9. In general, resonators are large and must therefore be integrated into the architectural design of a space. Exterior shapes can be altered, and the units can be installed less obtrusively to fulfill this architectural requirement.

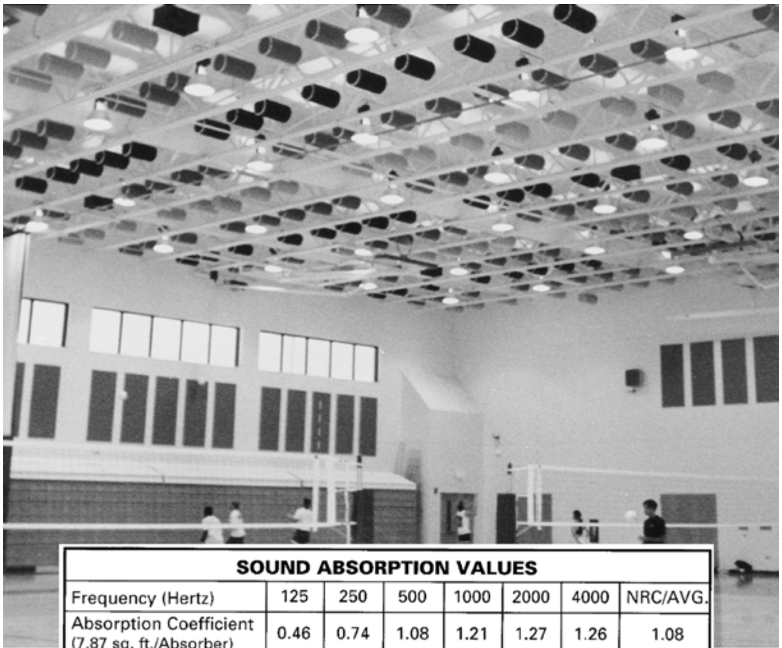
8. *Carpeting and drapery* can be used to cover large acoustically reflective surfaces in a space. Carpeting can be selected in almost any degree of density, looping, and depth, plus an additional depth of padding, to produce a high degree of absorption in middle and high frequencies (see Table 23.1). In general, absorption is proportional to pile height and density, and increases when the carpet is installed on a thick, fibrous pad. Where drapery is not feasible and wall panels are impractical, carpeting can be installed on walls. In such instances, installation on furring strips with an enclosed air space behind will increase absorption over the entire acoustic spectrum and especially at low frequencies (where direct-contact installation exhibits poor absorption). Draperies are essentially acoustically transparent and provide appreciable absorption only in the middle and upper frequencies with heavy, dense, fuzzy fabrics, particularly when draped with a high degree of fold. As with carpeting, absorption increases over the entire spectrum when a heavy folded drapery forms an air space between itself and the wall. Approximate absorption coefficients are given in Table 23.1.



(a)



(b)



SOUND ABSORPTION VALUES							
Frequency (Hertz)	125	250	500	1000	2000	4000	NRC/AVG.
Absorption Coefficient (7.87 sq. ft./Absorber)	0.46	0.74	1.08	1.21	1.27	1.26	1.08
Sabins/Absorber	3.65	5.84	8.48	9.51	9.98	9.90	8.45

(c)

Fig. 24.9 *(a) Resonator/absorber unit consists of a molded fiberglass cylinder, of 12-in. (305-mm) diameter and 24-in. (610-mm) length, containing a metal resonator at each end for low-frequency absorption and a fill of acoustic fiberglass for full-spectrum absorption. (b) The unit, which weighs about 6 lb (2.7 kg), is suspended on thin wires or chains that are essentially invisible when the unit is mounted 10 ft (3 m) above the finished floor (AFF) or higher. (c) A typical application in a school gymnasium. Because of their large size, the units constitute a major architectural element. By color selection and hanging patterns, they can be effectively used as such. The absorption characteristics of these units are listed in the table as a function of frequency. (Courtesy of The Proudfoot Co., Inc.)*

SOUND INSULATION

24.6 AIRBORNE AND STRUCTURE-BORNE SOUND

In contrast to the preceding material, which was concerned with in-room sound reduction by absorption, the following sections will discuss the characteristics of sound *transmission* between enclosed spaces. A distinction is often made between airborne and structure-borne sound, although in reality they differ only in the origin of the sounds. Airborne sound originates in a space with any sound-producing source, and although it changes to structure-borne sound when the sound wave strikes the room boundaries, it is still referred to as airborne because it originated in the air. *Structure-borne sound* is generally understood as energy delivered by a vibrating or impacting source directly contacting the structure. Hence, a child crying in an adjoining apartment is contributing airborne sound; the same child bouncing a ball on the floor is creating structure-borne sound, in this case by impact. Pumps that were installed without proper damping mounts create structure-borne sound by vibration.

In reality, all sound transmission is both airborne and structure-borne since, once having entered the structure, the sound travels along the structure and causes the structure to vibrate, in turn generating airborne sound. Figure 24.10 should assist in understanding this action. In Figure 24.10*a*, the sound is airborne, originating in the air on one side of the partition. The incidence of sound energy causes the partition to vibrate, generating sound on the other side. Sound does not "pass through" unless an air path exists. If the partition is airtight, then the sound energy causes the structure to become a secondary source. The partition vibrates primarily in the direction of the sound, that is, in the vertical plane. It also vibrates in other modes, causing some sound energy to pass into the floor and ceiling, depending upon the details of attachment. This energy becomes structure-borne sound.

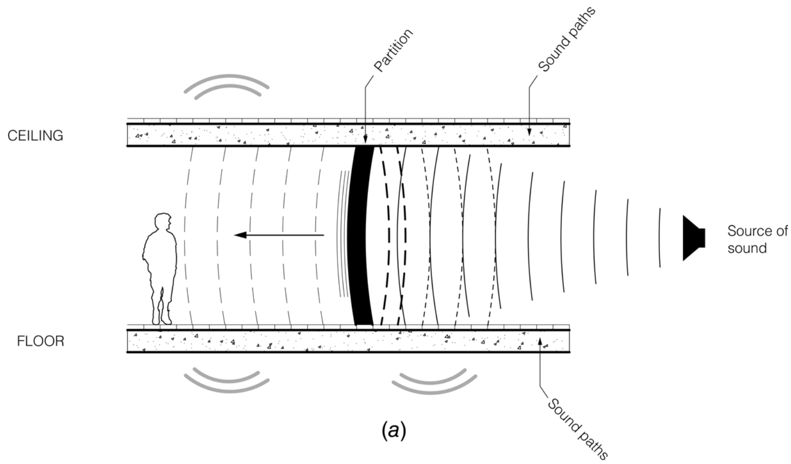
In Fig. 24.10*b*, the process is similar but reversed. Energy is introduced into the structure directly (and efficiently) by mechanical contact, that is, by vibration and impact. Sound travels along the structure, as shown, and, by causing the structure to vibrate, creates *airborne sound*. In a structure with rigid wall-to-floor connections, these sounds are clearly heard throughout the building. It is a common misconception that in a (relatively) massive concrete structure with masonry walls, such as a multistory residential building, light impacts such as footfalls will not be transmitted. On the contrary, the rigidity of the structure—in particular the rigid, airtight connections between partitions, floors, and ceilings—provides an excellent path for structure-borne sound. Only impact absorption by heavy carpeting will attenuate the sound of footsteps, and resilient floor-wall connections will attenuate structure-borne sound.

Airborne sound (originating in the air) is generally much less disturbing than structure-borne sound, since its initial energy is very small and it attenuates rapidly at boundaries. Structure-borne sound generally has a much higher initial energy level and attenuates slowly as it travels through a structure, thereby causing disturbance over large sections of a building. This disturbance is magnified by the "sounding board effect."

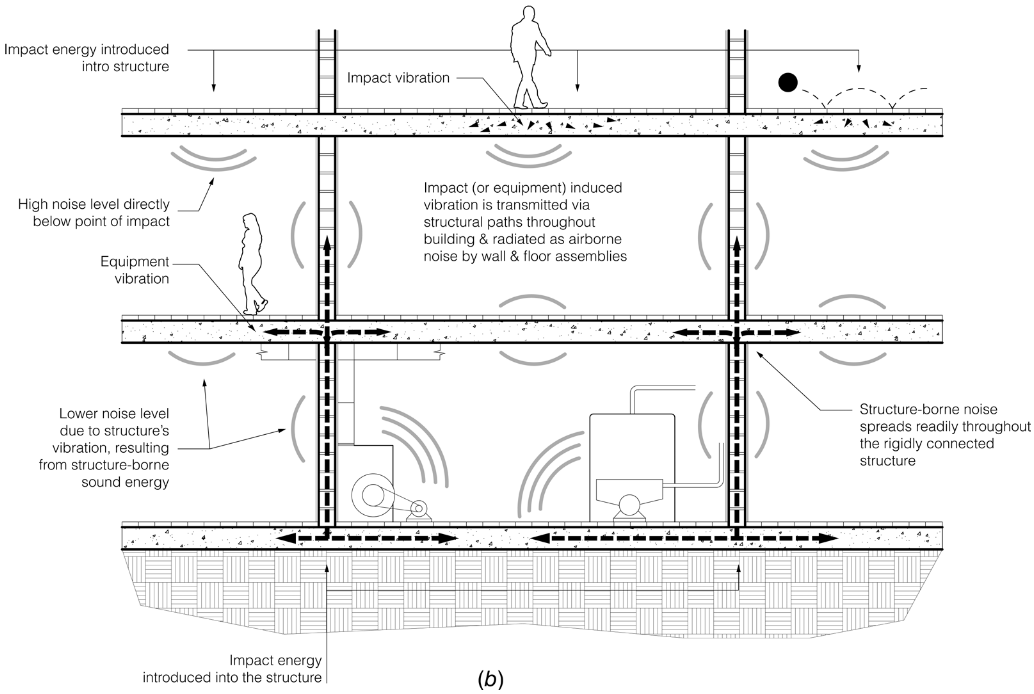
We are all familiar with the fact that a tuning fork must be held up to the ear to be heard directly, but if its handle is placed on a table the sound is amplified. This action is not really amplification but an increase in the efficiency of energy transfer. In general, the efficiency of a radiator is proportional to the ratio of its surface dimensions to the sound wavelength. A tuning fork vibrating at concert A (440 Hz) with a wavelength of 2.5 ft (0.75 m) cannot efficiently couple its energy into the air. It is simply too small. By placing the instrument on a table whose dimensions are approximately one wavelength, we permit it to transfer its energy efficiently, hence the amplification. The same effect can be extremely troublesome in structure-borne sound. A vibrating pump itself makes little sound. However, it transfers a large amount of energy into the structure, and that energy will appear as audible sound at each partition, floor, and wall that is rigidly coupled to the structure. Soft (damping) connections prevent energy transfer, thereby greatly attenuating the transmission of sound energy into connecting efficient radiating surfaces—hence the desirability of such flexible connections.

Airborne sound changes direction easily (diffracts), with low frequencies being most flexible in this regard. Structure-borne sound travels much more rapidly than airborne sound (see Table 22.1) and with attenuation as low as 1 dB per kilometer (about 0.5 dB per mile). A sound traveling along a massive structure will radiate outward from the structure only minimally (although enough to be very annoying) because the large mass minimizes vibration in that direction. Thus, in Fig. 24.10*b*, noise from impact on the floor above will be louder (for equal impact energy) than noise from machines below, because the former generates sound directly downward, while the latter introduces energy into the entire network of parallel paths.

The sections immediately following deal with airborne sound and the means for controlling it (Fig. 24.11). Impact noise (a form of structure-borne sound) is covered in Sections 24.22 to 24.34.



(*a*)



(*b*)

Fig. 24.10 *(a) Airborne sound is so called because it originates in air; its energy level is low. Here the loudspeaker is the source of acoustic energy, which is converted to a vibration of the partition (shown greatly exaggerated), which in turn becomes a secondary source of airborne sound for the adjoining space. A small amount of energy is reradiated by the ceiling and floor of both spaces directly, and indirectly via the rigid partition-to-floor and partition-to-ceiling connections. (b) Structure-borne sound originates from mechanical contact between the structure and vibrating or impacting sources. As a result, its energy level is usually much higher than that of airborne sound. This energy is transmitted with little attenuation throughout the structure via the rigid partition-to-floor and partition-to-ceiling connections. The entire structure is then set into vibration as shown, converting the (large) structure-borne sound energy to noise throughout the building. (Redrawn by Wesley Thompson from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*

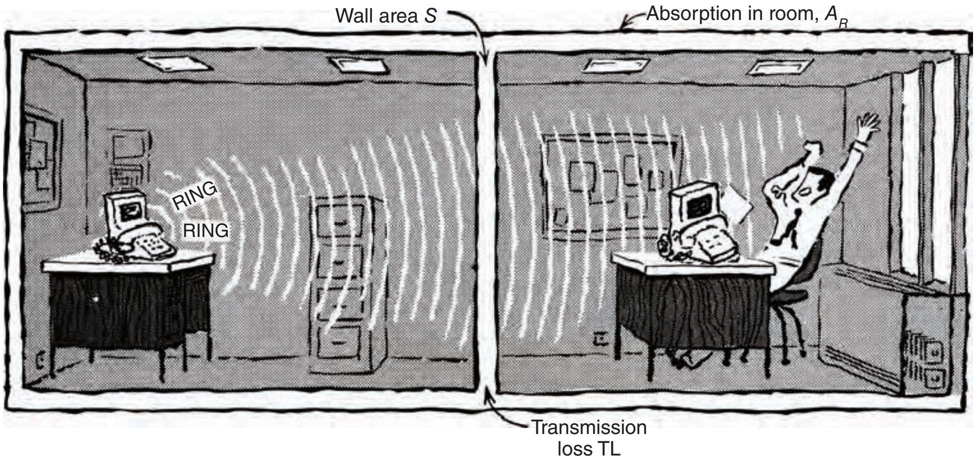


Fig. 24.11 *A simple case of airborne sound transmission between adjacent rooms through a common barrier. With a sound source in one room, the transmitted sound level is dependent not only on the transmission loss of the barrier but also on the area of the barrier and the receiving-room absorption. The background noise level in the receiving room determines whether the transmitted sound will be noticed.*

AIRBORNE SOUND

24.7 TRANSMISSION LOSS AND NOISE REDUCTION

The transmission loss (*TL*) of a barrier is the ratio, expressed in decibels, of the acoustic energy reradiated by the barrier to the acoustic energy incident on it. This number is a figure of merit for the sound-isolating quality of the wall itself and is obtained from controlled laboratory tests. (In Europe, transmission loss is referred to as *sound reduction index*, *R*.) However, the number that is of greater importance to the building designer is the actual noise reduction (*NR*) between two spaces separated by a barrier, that is, the action of the barrier in context. This noise reduction is defined as the difference between the sound intensity levels in the two rooms, that is,

$$NR = IL_{\text{room 1}} - IL_{\text{room 2}} \tag{24.2}$$

and is related to the *TL* of the barrier by the expression

$$NR = TL - 10 \log \frac{S}{A_R} \tag{24.3}$$

where

NR = noise reduction, dB
TL = barrier transmission loss, dB
S = area of the barrier, ft^2 (m^2)
A_R = total absorption of the *receiving* room, sabins, ft^2 (m^2)

We see, therefore, that noise reduction and transmission loss are not equal but are related by the size of the dividing barrier, *S*, and the absorption characteristic of the receiving room, A_R. A moment's thought will confirm the logic of this relation. When sound energy impinges on the barrier, the barrier in turn becomes the sound source, radiating into the receiving room. Therefore, the amount of sound energy transferred is proportional to the (log of) area *S* of the common barrier between the two spaces.

The sound level in the receiving room is related to its own reverberance (absorption characteristic, A_R), as we have seen repeatedly. Thus, if the receiving room is a reverberant, live space, A_R is low and *NR* is less than *TL*. Conversely, if the receiving room is dead, A_R is large and *NR* can be greater than *TL*, depending upon the ratio of the barrier wall size to the room area (see Fig. 24.11). In lieu of precise calculations, the following generalizations can be used:

1. For a live receiving room,

$$NR = TL - 1 \text{ dB}$$

2. For a medium receiving room,

$$NR = TL + 4 \text{ dB}$$

3. For a dead receiving room,

$$NR = TL + 7\ \text{dB}$$

The extreme case of "deadness" of a receiving room is one with no walls, that is, sound transmission from inside to the exterior. In such cases, *NR* exceeds *TL* by 10 to 15 dB, depending upon the size of the exterior opening and the point outside where *IL* is measured. To acquire facility with sound-insulation techniques, the designer must become familiar with the relationship of transmission loss to the barrier's physical characteristics: its mass, rigidity, material of construction, and method of construction and attachment. These considerations are the subject of the following sections.

Note: The reader is cautioned to be careful when encountering the term *noise reduction* (NR), since a similar and completely unrelated term—*noise reduction coefficient* (NRC)—also exists. The latter is very poorly named.

24.8 BARRIER MASS

Sound transmission between spaces requires that a barrier be set into vibration by the incident sound energy. Although this was stated in the preceding sections, we repeat it here to emphasize the fundamental importance of this simple statement. (We are assuming a barrier that is impervious to air—i.e., a solid barrier. Otherwise, the moving air molecules bearing the sound will simply pass through with minimal transmission loss.) The impinging sound energy acts as a force on the wall. Since $F = MA$, the larger the mass, the less it will vibrate. When other factors (particularly angle of incidence) are taken into account, the resultant acoustical relationship is known as the *mass law*. It states that for a nonporous, homogeneous structure of low stiffness, the sound transmission loss is proportional to the logarithm of the surface mass (the weight of the wall per unit of surface area) and to the frequency of vibration. Thus, doubling the mass (or frequency) will, theoretically, cause an increase of 6 dB in the transmission loss; stated otherwise, the slope of *TL* versus the frequency times mass (*fM*) curve is 6 dB. Figure 24.12 is a graphic representation of mass law operation. With sound incident at 9°, maximum energy is imparted to the barrier, and the entire mass resists, resulting in maximum transmission loss. In practice, however, sound is incident from 0° to 80° (called *field* or *random incidence*), reducing the mass effect but keeping the slope at 6 dB per octave. Due to nonhomogeneity, porousness, and stiffness, actual field results indicate transmission losses closer to 4 dB per octave, as shown by the lower curve in Fig. 24.12.

24.9 STIFFNESS AND RESONANCE

The *stiffness* of a barrier is a function of its material composition and the rigidity of its mounting. The former depends upon its internal cohesiveness—that is, its modulus of elasticity—and the latter depends upon its boundary restraints—whether the barrier is tightly or loosely held. A homogeneous material of high Young's modulus (such as steel) has great cohesiveness between its molecules. As soon as one molecule is set in motion by incident sound energy, the motion is passed to the next molecule, and so on, making the material an excellent sound conductor. Homogeneous materials with a low modulus of elasticity have high internal damping (the motion of molecules is not transmitted well), and they are good sound insulators. Composite materials such as concrete and organic materials such as wood do not conform to these general rules.

Rigidity of mounting can be likened to a drumhead—the tighter it is stretched, the better it resounds. Rigidity (stiffness) in a panel barrier resists damping and assists vibration, making it a good transmitter and, conversely, a poor noise transmission insulator. As a result, a material such as lead, which has a high mass and a low modulus of elasticity and resists rigid mounting, is an excellent sound attenuator.

The effects of stiffness and mass both vary with frequency, unfortunately in opposite directions. Stiffness acts to reduce transmission loss as frequency increases, while, as we have seen, mass acts to increase it; the combined effect is shown in Fig. 24.13. Therefore, stiffness is most effective at low frequencies and mass at high frequencies. At very low frequencies the mass and stiffness effects negate each other, giving the resonance dips shown. Beyond approximately 200 Hz, most common wall construction enters the mass law range and continues with it until the critical frequency. Deviations

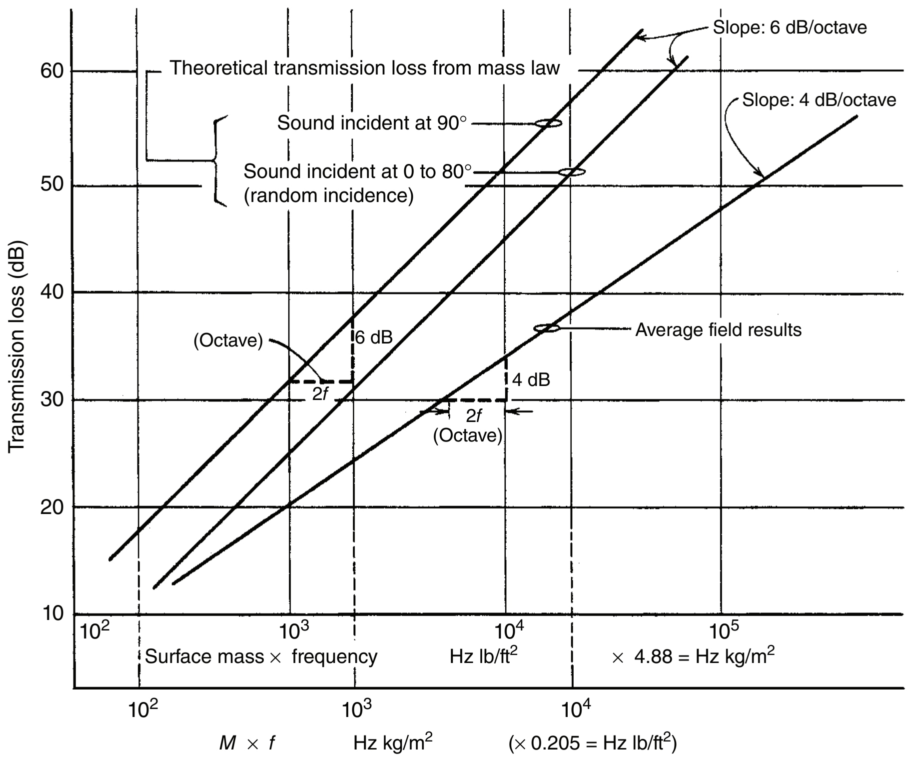


Fig. 24.12 *Graphic representation of mass law action in attenuation of transmitted sound. Perpendicular (90°) sound incidence results in maximum transmission loss. Field or random incidence (0° to 80°) is approximately 6 dB lower but maintains the 6-dB-per-octave slope. Field results are lower due to flanking and stiffness effects, and the slope of the curve averages only 4 dB per octave (frequency doubling).*

from a smooth 4-to-6-dB-per-octave slope are due to the non-homogeneous nature of most wall constructions. At the *critical frequency* the phase of incident sound waves corresponds to or coincides with the phase of vibration (shear wave) of the barrier in such a way as to pass a large portion of the incident energy. See the insert in Fig. 24.13, which shows this effect as the coincidence dip. This effect is most pronounced in thin, homogeneous partitions and light, stiff ones.

Critical frequency, f_c, as a function of panel thickness for common materials, is plotted in Fig. 24.14. To avoid a coincidence dip in the audible range, partitions can be either very heavy and/or very stiff (which greatly decreases the critical frequency) or heavy and limp (resilient—which greatly increases the critical frequency). In practical terms, cost effectiveness is heavily in favor of the latter alternative. Thus, for instance, the transmission loss of a wood partition can be improved by grooving it to increase its flexibility, thereby increasing the critical frequency. The dramatic improvement in transmission loss, resonances, and coincidence dip achieved by the use of resilient mounting of a simple masonry partition is shown in Fig. 24.15. Both walls have the same weight—21 lb/ft^2 (102 kg/m^2). The solid wall *A* has better attenuation below 200 Hz in the stiffness-controlled range. Above that frequency the resilient-mounted partition is 10 dB better, which means that the transmitted noise is only one-half as loud. The sound transmission class (STC) (which is a figure of merit for partition sound transmission, as explained in Section 24.11) of wall A is 40; that of wall B is 51. Both show a coincidence dip at approximately 250 Hz (see Fig. 24.14), but that of B is shallow, whereas that of A is deep and wide. Furthermore, wall B is consistently better than mass law attenuation would predict, wall A consistently worse (due to stiffness).

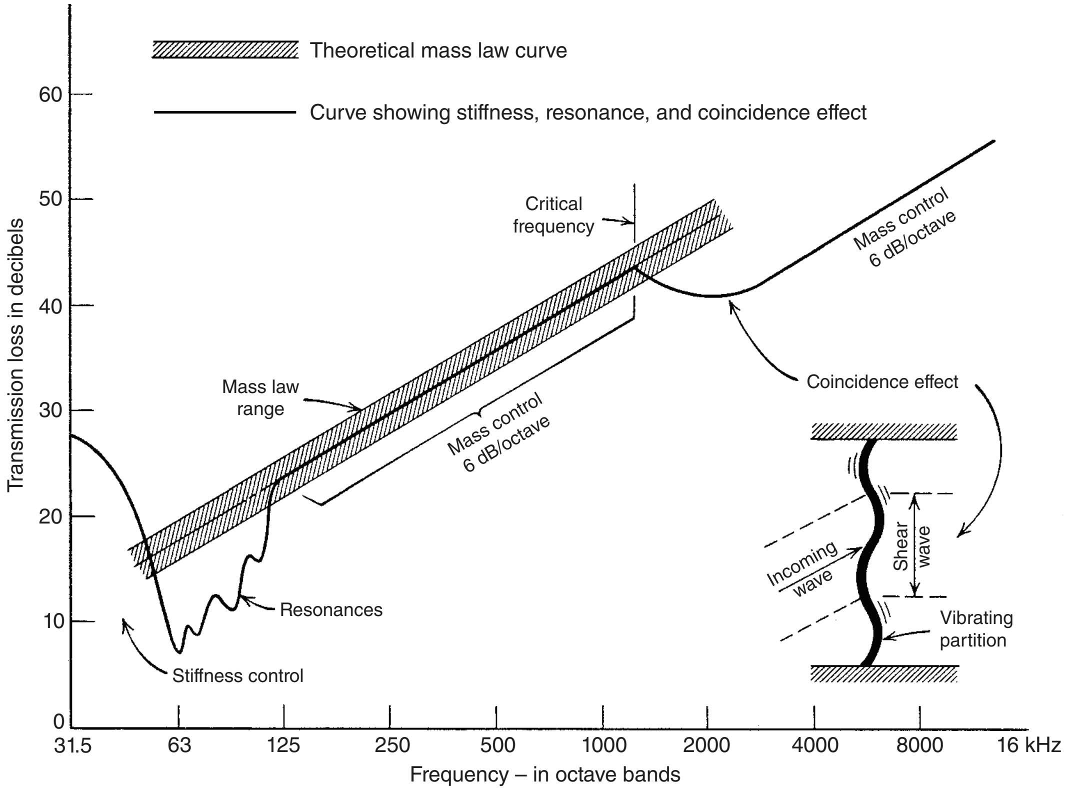


Fig. 24.13 *Partition transmission loss as a function of frequency showing the effects of stiffness, resonance, and coincidence. At frequencies below resonance, control is almost purely a stiffness function; at frequencies above critical, control is almost purely a surface mass function.*

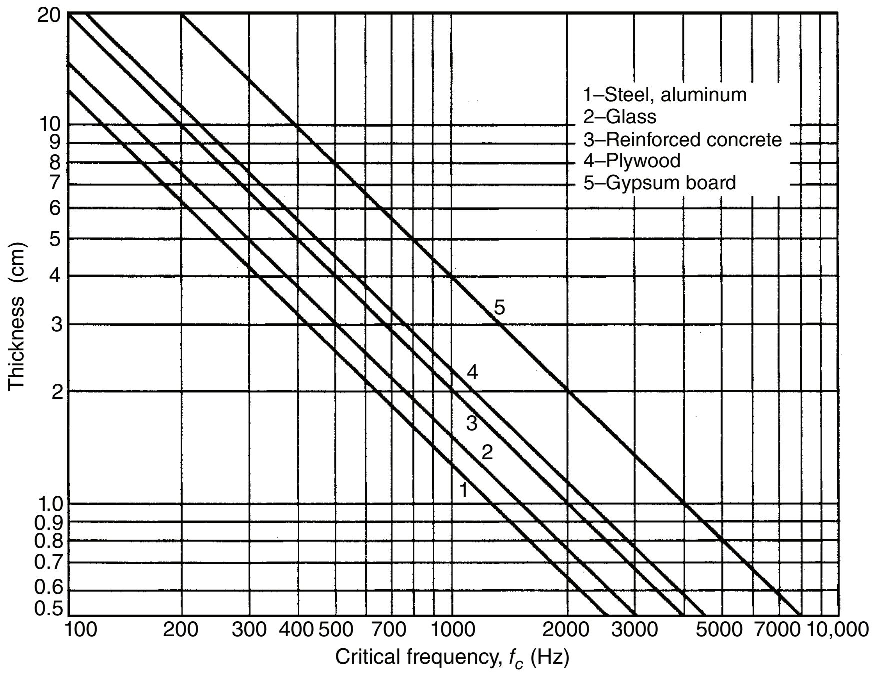


Fig. 24.14 *Critical frequency as a function of thickness for several common materials. (Reprinted with permission from E. B. Magrab. 1975.* Environmental Noise Control*. John Wiley & Sons. Hoboken, NJ.)*

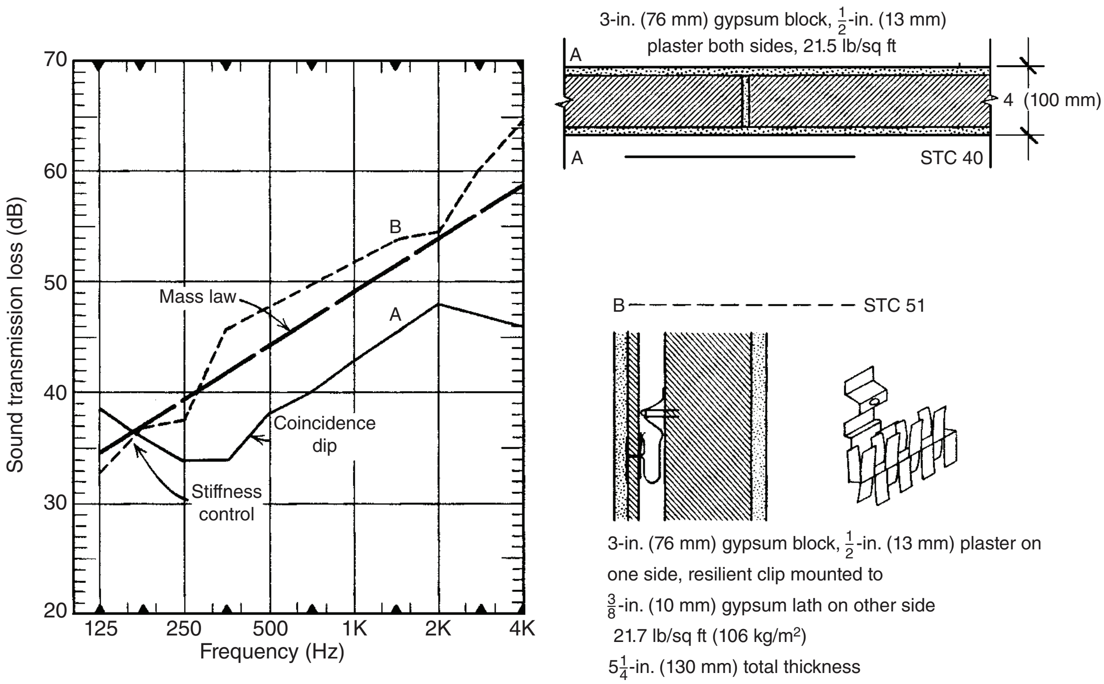


Fig. 24.15 *Transmission loss characteristics of two equal-weight partitions with similar boundary constraints. The solid partition A performs worse than the mass law, due to stiffness. The resilient-mounted wall B performs better than the mass law and much better than wall A, except at the lowest frequencies. (Data extracted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*

24.10 COMPOUND BARRIERS (CAVITY WALLS)

Since the maximum theoretical increase in transmission loss with an increase of mass is 6 dB per doubling of mass, adding more mass as a means of transmission loss improvement rapidly reaches the limits of practicality. Indeed, as we have seen, the transmission loss of actual single homogeneous walls falls below the mass law curve. This is because mass increase brings with it stiffness increase, which acts to *reduce* transmission loss. If, however, a barrier is constructed of two separate layers without rigid interconnection, its performance exceeds the calculated transmission loss based on mass alone. Note that even the nonrigid wire ties of wall B in Fig. 24.16 lower the STC by five points. At low frequencies, where stiffness controls the transmission loss (see Fig. 24.13), the cavity in wall C (Fig. 24.16) acts as a rigid connection between the layers, adding stiffness and increasing transmission loss. At higher frequencies, in the mass law range, the air in the cavity acts as a damping coupling to reduce stiffness. The net result is an improvement in performance throughout the frequency range.

Transmission loss for the entire cavity wall increases with the width of the air space at the rate of approximately 5 dB per doubling. Performance can be improved still further by filling the void with porous, sound-absorbent material. This acts to further decrease the stiffness of the compound structure *and* to absorb sound energy that reflects back and forth between the two inside surfaces. The performance of cavity walls is reduced by any rigid interconnections between leaves. Thus, a common stud wall with frequent rigid interconnections acts little better than a single homogeneous wall. However, a stud wall with staggered studs exhibits greatly improved performance over a single-material wall or a common stud wall. These effects are illustrated in Figs. 24.16 and 24.17 (see also Appendix K). The effects of mass (Section 24.8), stiffness (Section 24.9), and compound barriers with and without filler are shown qualitatively and graphically in Fig. 24.18.

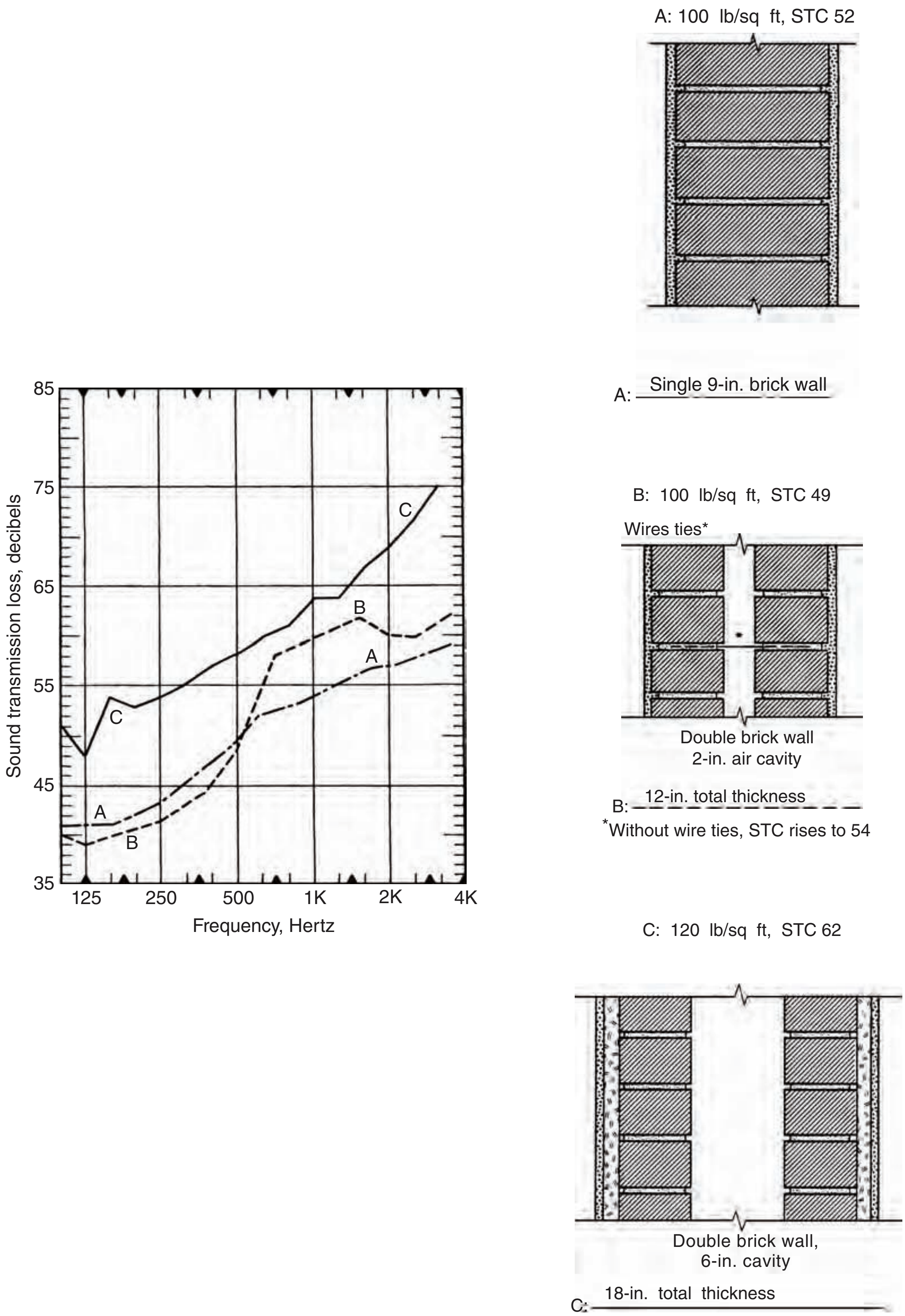


Fig. 24.16 *Transmission loss curves showing the effect of air space on heavy wall construction. All three walls are approximately the same mass. The 2-in. (50-mm) air space of wall B is not significant until the higher frequencies, whereas the large 6-in. (200-mm) air space of wall C is effective throughout the frequency spectrum. (Data extracted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD, 1968.)*

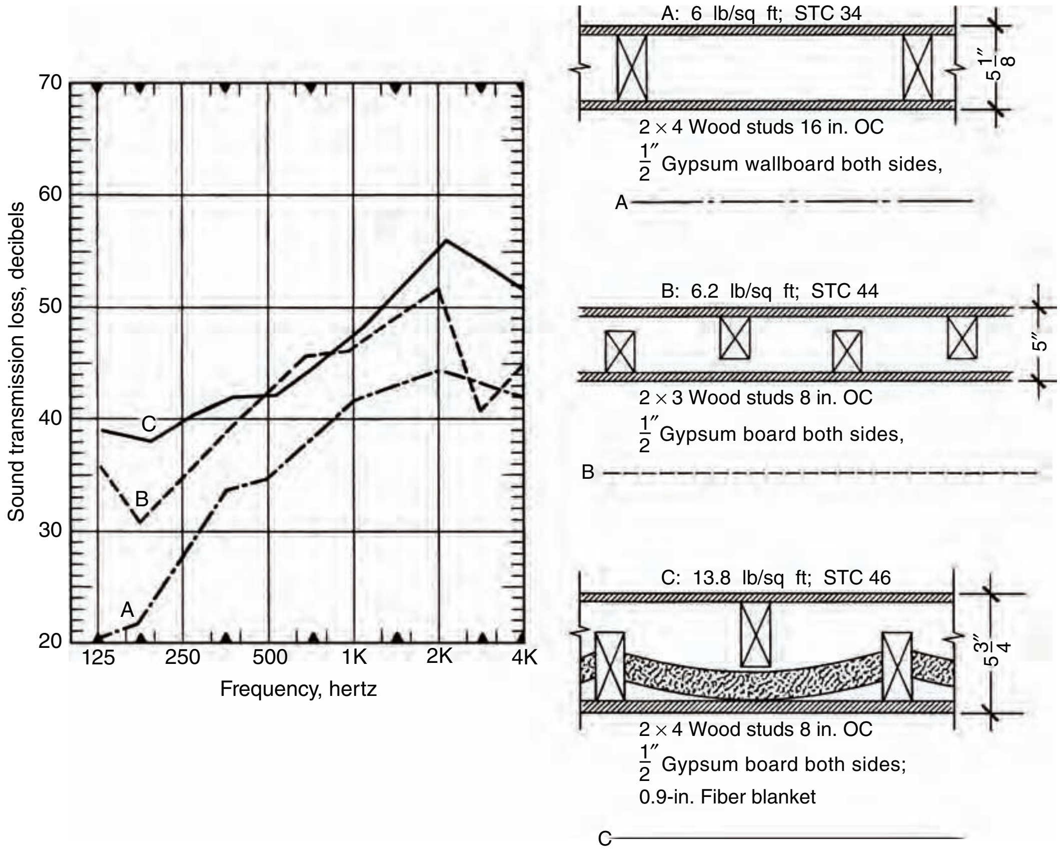


Fig. 24.17 *Transmission loss curves illustrating the effect on lightweight walls of stiffness reduction and addition of absorptive material in the cavity. Curve A is a standard stud wall typically found in frame construction. Curve B shows the advantage of staggered studs over the entire frequency range. The dip at 3 kHz is a coincidence dip for a single leaf. Addition of absorptive material (curve C) improves the attenuation characteristic at both ends of the spectrum and is particularly useful for its low-frequency improvement. (Data extracted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD, 1968.)*

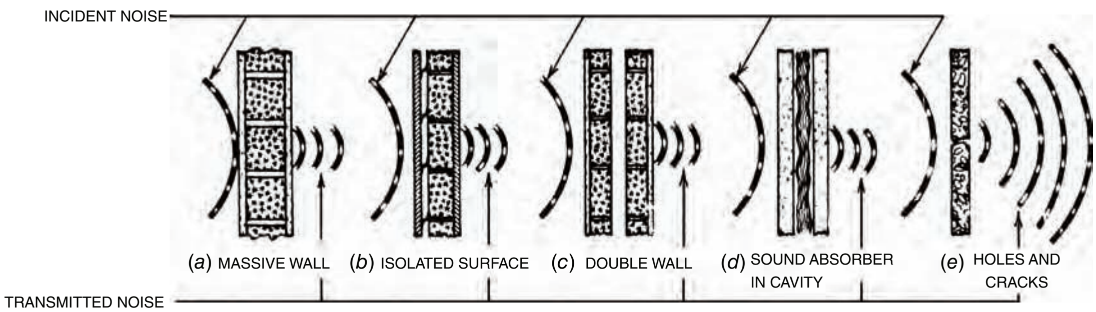
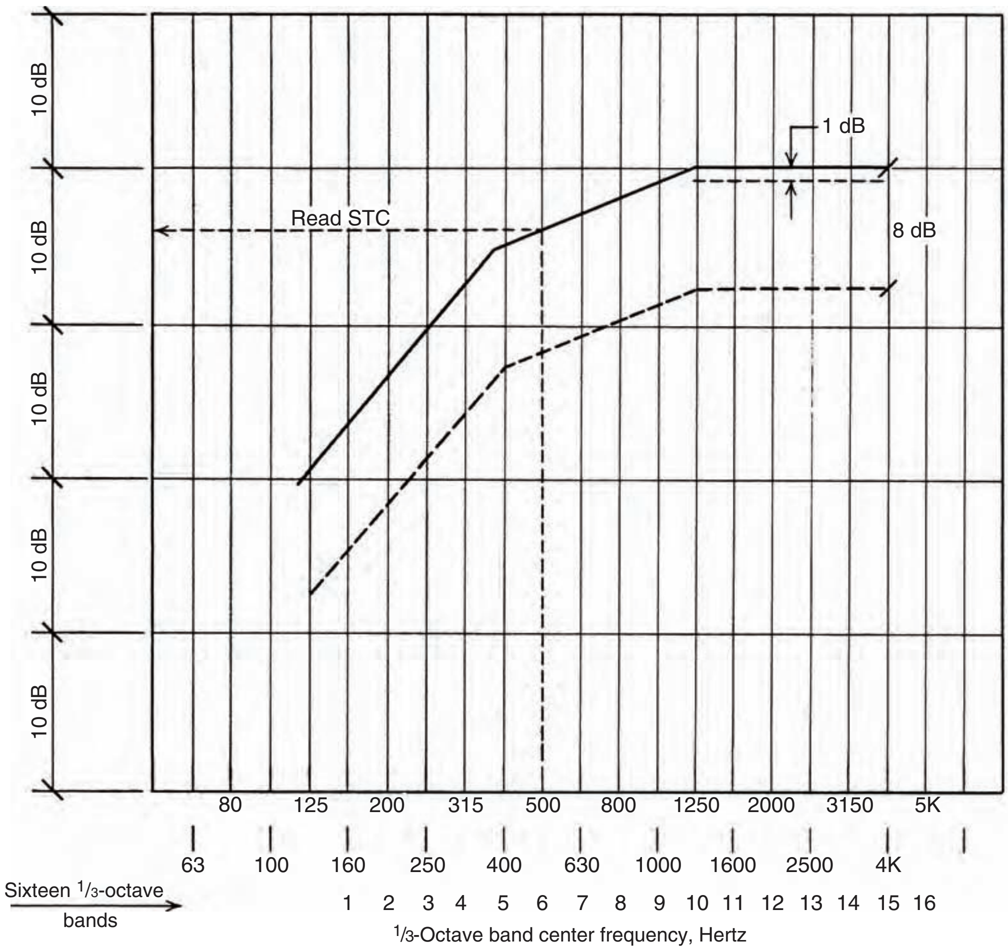


Fig. 24.18 *The various techniques used to increase the transmission loss of a partition are shown in (a–d). In contrast, even a very small air path through the partition (e) can effectively destroy its effectiveness as a sound barrier. (Data extracted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD, 1968.)*

24.11 SOUND TRANSMISSION CLASS

Various attempts at using a single-number average transmission loss to describe a barrier's characteristics have been made, with only limited success. Indeed, such averages can be misleading, since they ignore both deficiencies and proficiencies at particular frequencies. Their use, therefore, in all but rough work, is to be discouraged.

To avoid the shortcomings of averages and yet to benefit from the indisputable convenience of single-number ratings, a system of standard contours was developed in the United States called *sound transmission class* (STC) contours. (A similar



The STC is determined by comparison with a transparent overlay of this graph on which the STC contour is drawn. The STC contour is shifted vertically, relative to the test curve, until some of the measured *TL* values for the test specimen fall below those of the STC contour (the soild line) and the following conditions are fulfilled:

1. The sum of the deficiencies (i.e., the deviations below the contour) shall not be greater than 32 dB.
2. The maximum deficiency at a single test point shall not exceed 8 dB [the broken (dashed) line beneath the STC contour].

When the contour is adjusted to the highest value (in integral dB) that meets the above requirements, the sound transmission class for the specimen is the *TL* value corresponding to the intersection of the contour and the 500-Hz ordinate.

Fig. 24.19 *Overlay from which sound transmission class (STC) is determined graphically.*

system, conforming to ISO 717-1, 2013, is used in Europe, involving a weighted sound reduction index R_W.) In practice, the STC number for a particular barrier construction is derived by comparing actual test results measured in a series of sixteen ⅓-octave bands to the standard STC contours according to a fixed procedure. The technique is illustrated in Fig. 24.19. Figure 24.20 shows two transmission loss curves and STC ratings of each. Because STC fails to give credit for performance *above* the established requirements, octave band transmission loss data, rather than STC ratings, should be used in all critical areas such as music rooms or mechanical rooms where certain particular frequencies may be dominant.

Figure 24.21 gives three standard STC contours that are of interest because they are used

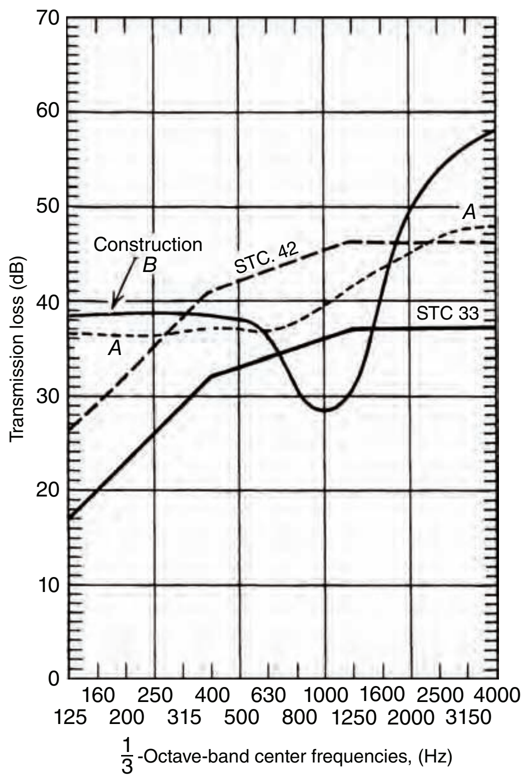


Fig. 24.20 *Curves* A *and* B *are two different construction types with the same average transmission loss. However, application of the STC curve criteria (given in Fig. 24.19) yields an STC of only 33 for construction* B *because of its deep center dip, compared to an STC of 42 for construction* A*. (From E. B. Magrab 1975.* Environmental Noise Control*. John Wiley & Sons. Hoboken, NJ.)*

by the Federal Housing Administration (FHA) to specify grades of construction. The criteria for their application are found in Section 24.33. An appreciation of the degree of speech sound isolation provided by walls with different STC ratings is given in Section 24.17 (see Table 24.5). Since the subjective reaction on the quiet side depends upon the background sound level, the table gives this reaction for two NC curve levels. To assist the designer, extensive sound transmission testing has been performed on most types of standard wall and partition construction and the results published. Tables 24.1 and 24.2 and Appendix K give descriptions of constructions with typical details, transmission loss data, STC ratings, and other pertinent data.

24.12 COMPOSITE WALLS AND LEAKS

It is frequently necessary to determine the transmission loss of a composite wall—that is, a wall with a window, door, louver opening, and the like. It should be appreciated that the two elements are "in parallel," to borrow an electrical concept, and the acoustical behavior is similar to that situation. That is, the overall performance will be strongly affected by the poorer of the two, with some tempering of the degradation when the poorer barrier is much smaller in area than the other barrier element. Figure 24.22 enables us to analyze situations of this type.

Since an opening in a wall is effectively a second material of $TL = 0$, the curves in Fig. 24.22 can be replotted for this situation as in Fig. 24.23. Note that the curves very rapidly flatten out; thus, any wall with a 1% open area will have a *maximum* transmission loss of 20 dB, which makes it all but useless as a sound barrier. For this reason, it is imperative that all openings be completely sealed, particularly those around doors and windows. A hairline crack degrades a wall 6 dB, a keyhole degrades a door 3 dB, and so on. Special considerations for doors and windows are discussed in the next section. Care must also be taken with such common acoustic leaks as back-to-back electric outlets, pipes passing through walls, and medicine cabinets—in fact any break in the integrity of a partition. All such openings must be caulked to make an airtight joint if any appreciable degree of sound insulation is to be maintained.

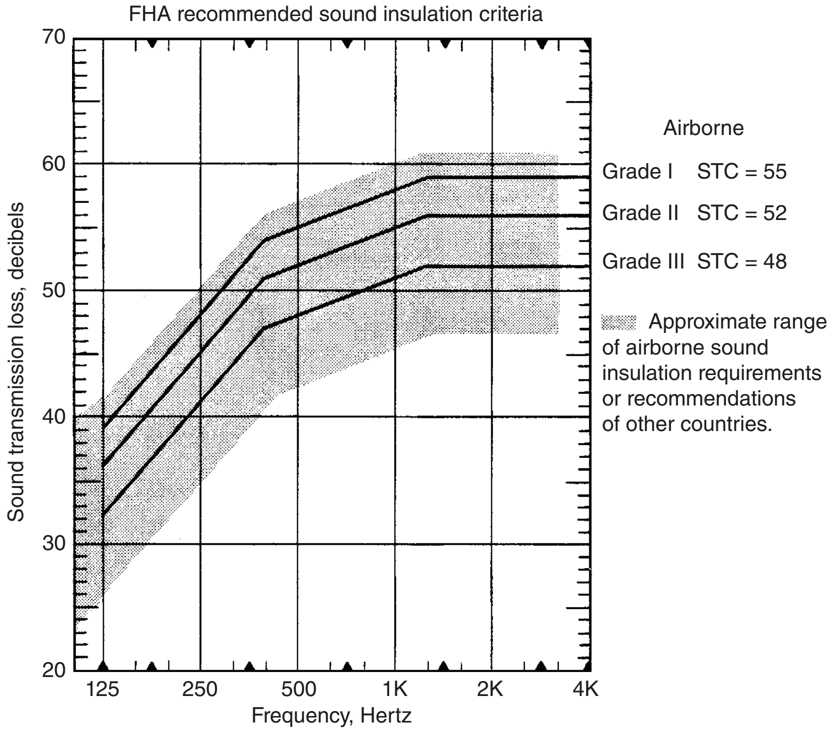


Fig. 24.21 *Sound insulation criteria recommended by the FHA. (From* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*

TABLE 24.1 Improvements in STC Rating of Stud[a] Partitions[b]

Description	STC[c]
Basic partition: single wood studs, 16 in. (406 mm) on center, ½-in. (13-mm) gypsum board on both sides, air cavity	35
Add to basic partition	
Double gypsum board, one side	+2
Double gypsum board, both sides	+4
Single-thickness absorbent material in air cavity	+3
Double-thickness insulation	+6
Resilient channel supports for gypsum board	+5
Staggered studs	+9
Double studs	+13

[a]For application to metal stud partitions, use adders as in note b, but begin with STC = 40 for a 3⅝-in. (92-mm) basic partition.

[b]When using two improvements, add an additional +2; for three improvements, add +3.

Example: Improvements to 35 STC basic partition:

Staggered wood studs	+9
Double gypsum board, one side	+2
Single-thickness insulation	+3
Adder (3 improvements)	+3
Total	+17
Total STC	35 + 17 = 52

[c]The STC figures are conservative. Other sources list the same constructions with 1 to 5 points higher STC.

TABLE 24.2 STC Ratings of Masonry Walls

Description	STC[a]
4-in. (102-mm) lightweight[b] hollow block	36
4 in. (102-mm) dense hollow block	38
6-in. (152-mm) lightweight hollow block	41
6-in. (152-mm) dense hollow block	43
8-in. (203-mm) lightweight hollow block	46
8-in. (203-mm) dense hollow block	48
12-in. (305-mm) lightweight hollow block	51
12-in. (305-mm) dense hollow block	53
4-in. (102-mm) brick	41
6-in. (152-mm) brick	45
8-in. (203-mm) brick	49
12-in. (305-mm) brick	54
6-in. (152-mm) solid concrete	47
8-in. (203-mm) solid concrete	50
10-in. (254-mm) solid concrete	53
12-in. (305-mm) solid concrete	56

[a]See note c, Table 24.1.

[b]All ratings of lightweight block assume sealing with paint. Note that this reduces absorption.

Modifications

Add sand to cores of hollow blocks	+3
Add plaster to one side	+2
Add plaster to both sides	+4
Add furring strips, lath and plaster:	
One side	+6
Two sides	+10
Add plaster via resilient mounting:	
One side	+10
Two sides	+15

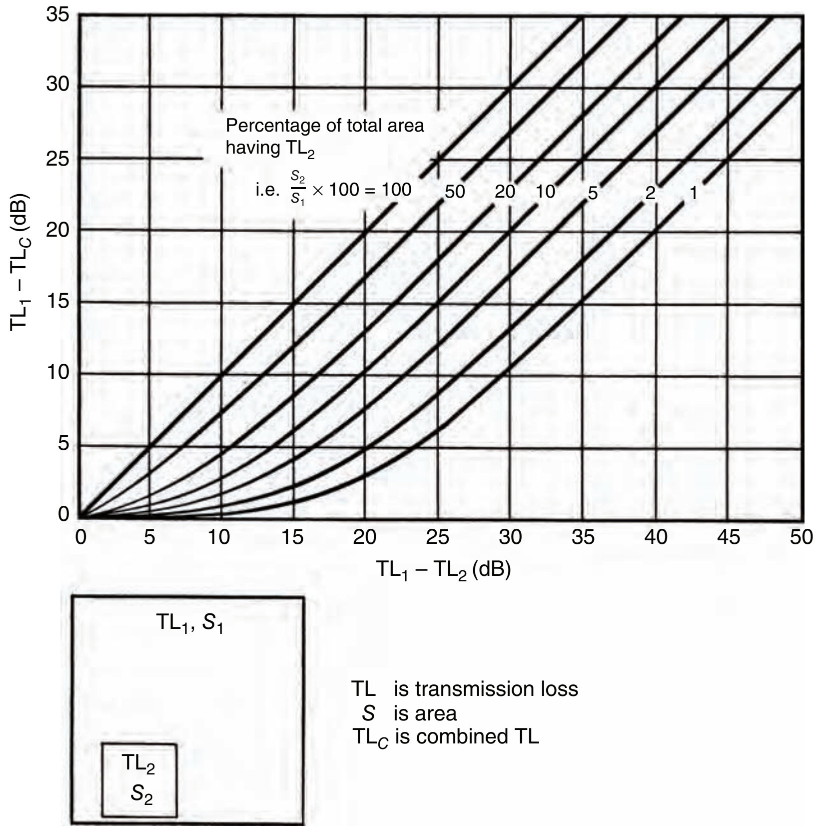


Fig. 24.22 *Transmission loss of a two-element composite barrier as a function of the relative transmission loss of the components. (From E. B. Magrab. 1975.* Environmental Noise Control. *John Wiley & Sons. Hoboken, NJ.)*

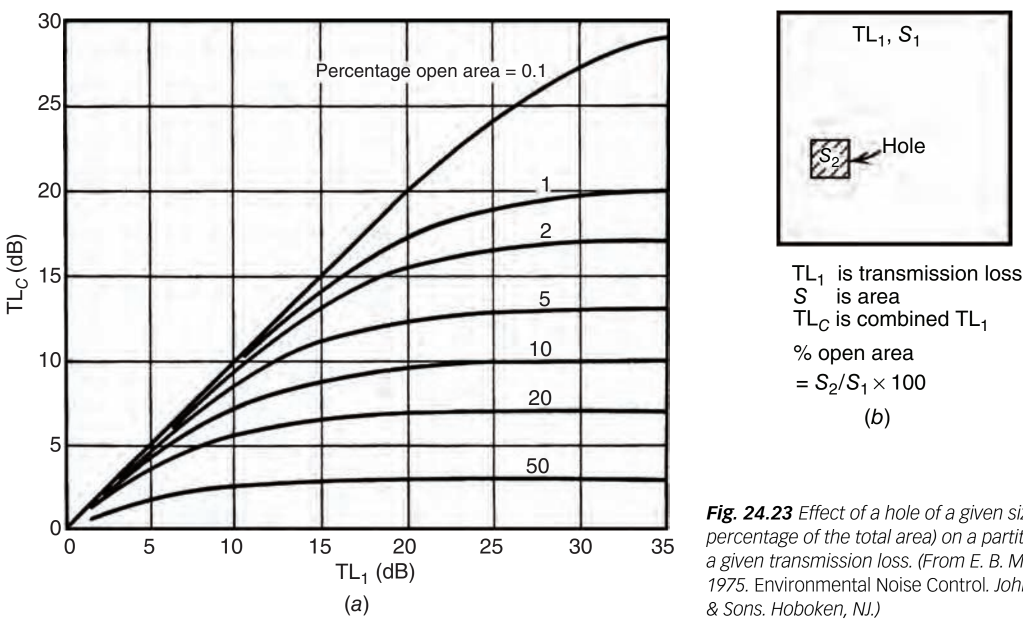


Fig. 24.23 *Effect of a hole of a given size (as a percentage of the total area) on a partition with a given transmission loss. (From E. B. Magrab. 1975.* Environmental Noise Control. *John Wiley & Sons. Hoboken, NJ.)*

Examples 24.1 and 24.2 show how barriers of high transmission loss are degraded by standard openings. To maintain the integrity of a barrier, special care must be taken in the design of windows and doors, as explained in Section 24.13.

EXAMPLE 24.1 Given a 9-ft × 18-ft (2.7-m × 5.5-m) wall with a transmission loss of 52 dB at 1000 Hz, containing a 3-ft × 7-ft (0.9-m × 2.1-m), 6-in. (150-mm) hollow core door of 22 dB transmission loss at that frequency, find the overall transmission loss of the composite wall.

SOLUTION

Refer to Fig. 24.22.

$$TL_1 - TL_2 = 30 \text{ dB}$$

$$\frac{S_2}{S_1} = \frac{3 \times 7.5}{9 \times 18} \times 100 = 13.9\%$$

From the curves in Fig. 24.22:

$$TL_1 - TL_c = 21.5$$

$$TL_c = 52 - 21.5 = 30.5 \text{ dB}$$

That is, a door with an area of only 14% of the entire wall reduces the transmission loss of the structure from 52 to 30.5 dB—that is, from excellent to very poor. ■

EXAMPLE 24.2 An exterior brick/frame wall having a transmission loss of 54 dB at 1000 Hz, measuring 8 ft × 16 ft (2.4 ft × 4.9 m), is pierced by two wood-frame windows, each of area 3 ft × 4 ft (0.9 m × 1.2 m), with single ⅛-in. (3 mm) glass, with a transmission loss of 34 dB at 1000 Hz. Find the combined transmission loss.

SOLUTION

$$TL_1 - TL_2 = 54 - 34 = 20 \text{ dB}$$

$$\frac{S_2}{S_1} = \frac{2 \times 3 \times 4}{8 \times 16} \times 100 = 18.8\%$$

From Fig. 24.22:

$$TL_1 - TL_c = 12.5 \text{ dB}$$

$$TL_c = 54 - 12.5 = 41.5$$

Again, the result is a reduction from an excellent wall to a poor one. ■

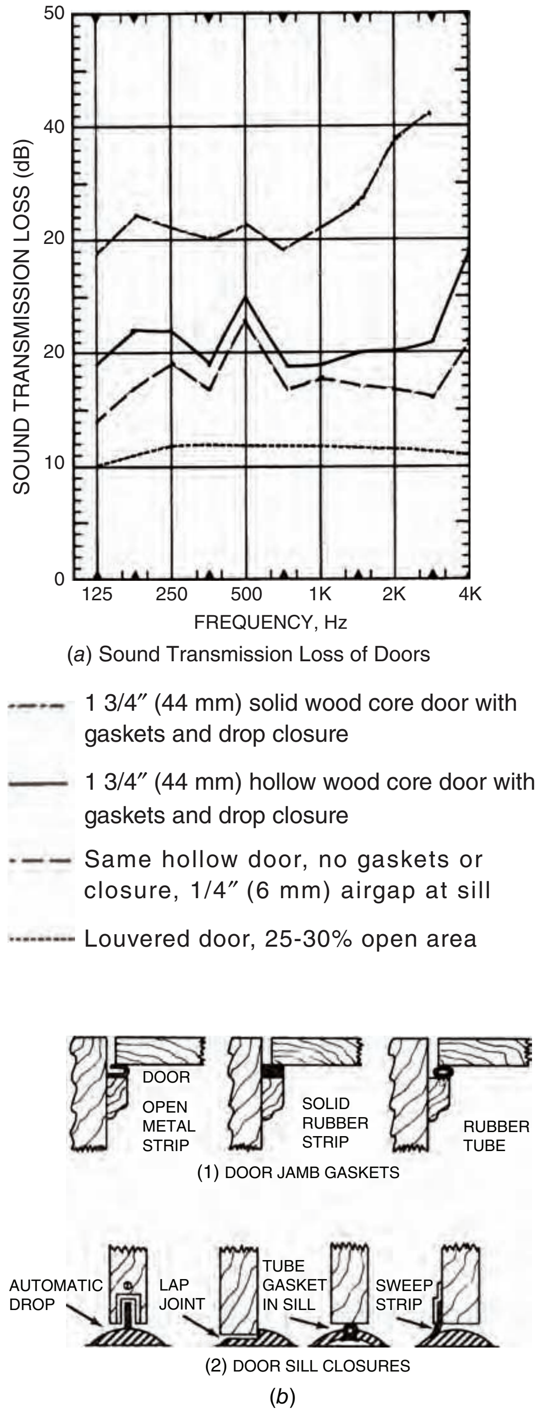


Fig. 24.24 *(a) Chart of typical transmission loss values for representative door constructions as a function of frequency. (b) Method for gasketing a door edge enclosure (1) and sealing the gap between the bottom of the door and the door saddle (2). (Chart and drawings extracted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*

24.13 DOORS AND WINDOWS

As can be appreciated from the preceding section, doors and windows can in large measure determine the overall transmission loss of a wall. Since in almost every instance doors and windows have a lower acoustic transmission loss than the wall in which they are mounted, particular care must be taken not to degrade performance further with air leaks.

(a) Doors

Figure 24.24 gives nominal transmission loss data for the most common types of doors as a function of frequency. Average transmission loss values for doors—that is, the arithmetic average of the octave band transmission losses in the range of 150 Hz to 3000 Hz—are not useful, for two reasons:

- The very important low-frequency attenuation data are absent.
- Sharp peaks and valleys in the curves (see, for instance, the 6-dB peaks at 500 Hz in Fig. 24.24*a*) are unrecognized. As a result, a particularly troublesome frequency may not be sufficiently attenuated. In the absence of a complete frequency analysis, the STC rating of a door is a better indication than an average transmission loss figure. Typical STC values are given in Table 24.3.

Conclusions that can be drawn from inspection of Fig. 24.24*a* are:

1. Louvered doors (and doors undercut to permit air movement) are useless as sound barriers.
2. The most important step in soundproofing doors is complete sealing around the opening. A door in the closed position should exert pressure on gaskets, making the joints airtight (see Fig. 24.24*b*).

TABLE 24.3 Typical STC Values for Doors

Door Construction	STC
Louvered door	15
Any door, 2-in. (51-mm) undercut	17
1½-in. (38-mm) hollow core door, no gasketing	22
1½-in. (38-mm) hollow core door, gaskets and drop closure	25
1¾-in. (45-mm) solid wood door, no gasketing	30
1¾-in. (45-mm) solid wood door, gaskets and drop closure	35
Two hollow core doors, gasketed all around, with sound lock	45
Two solid core doors, gasketed all around, with sound lock	55
Special commercial construction, with lead lining and full sealing	45–65

When a single door does not provide sufficient attenuation, and specially constructed high-attenuation commercial acoustic doors are not practical, a simple and very effective technique is the construction of a sound lock consisting of two doors, preferably with sufficient space between them to permit full door swing (see Fig. 24.25). All surfaces in the sound lock should be covered completely by absorbent material and the floor carpeted. Such an arrangement will increase attenuation across the spectrum by at least 10 dB and by as much as 20 dB at some frequencies, depending upon the shape of the sound lock and the type, amount, and mounting of absorptive material in the sound lock. The two doors of the sound lock must be gasketed, as explained in the preceding discussion.

Another important consideration with respect to sound intrusion via doors is the location of a door relative to sources of unwanted sound. This is particularly important in multiple-resident buildings of all types, including private homes, apartment

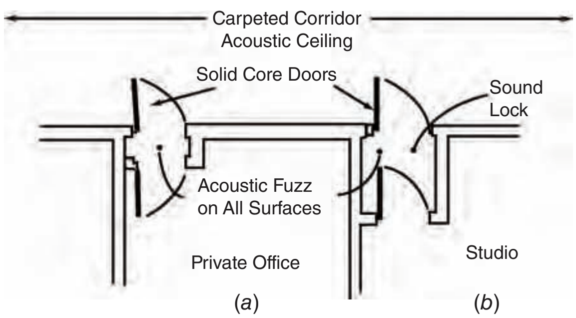


Fig. 24.25 *A two-door sound lock should increase the transmission loss of a door assembly by a minimum of 10 dB for the small lock (a) and 15 dB for the larger one (b), depending upon the type, thickness, and mounting technique of the absorptive material in the lock. The solid core doors must be sealed by one of the techniques shown in Fig. 24.24(b).*

houses, dormitories, hotels, and rooming houses. The same principle applies to commercial spaces where numerous private spaces such as offices open onto a common lobby or foyer. Figure 24.26 shows options for improvements in door placement.

(b) Windows

Windows are critically important to block exterior noise, and all the more so, since exterior wall construction is generally of high STC, making the window the deciding factor in the composite exterior wall transmission loss. Sound leaks through cracks in closures of operable windows will normally establish a window's rating, regardless of the type of glazing. Fortunately, the attention now given to the sealing of windows for thermal purposes has had a positive effect on their acoustic properties. As with doors, the importance of proper gasketing and sealing cannot be overemphasized. Double glazing is effective only when the two panes are separated by a wide air gap (Fig. 24.27). A narrow air gap acts as a stiff spring between the panes and transmits sound energy almost unattenuated. The result is approximately that of a single pane of double weight. Note that here too, as with absorptive material, the requirements of acoustic and thermal insulation are opposed. A small sealed air space between panes is desirable for thermal insulation, because a large space allows convection currents to transfer heat. For acoustical purposes, a small sealed space is not very useful, as explained previously, whereas a large space traps acoustic energy and is an effective noise barrier, as is clearly seen in Fig. 24.28.

In addition to a window's sound transmission characteristic when closed, it is important to consider the transmission loss when open to accommodate ventilation and passive cooling requirements. The sound attenuation between the center of a room with a clear-through open window and a point some distance outside is 5 to 15 dB. This drops to about 5 dB as the receiver-observer approaches the open window. By making the path from inside to outside indirect, the open window attenuation can be increased to as much as 25 dB, but with considerable reduction of airflow and hence ventilation capacity. Several possible arrangements with approximate midfrequency transmission loss figures are given in Fig. 24.29. This principle can be applied advantageously when exterior noise reduction is important but sealed windows

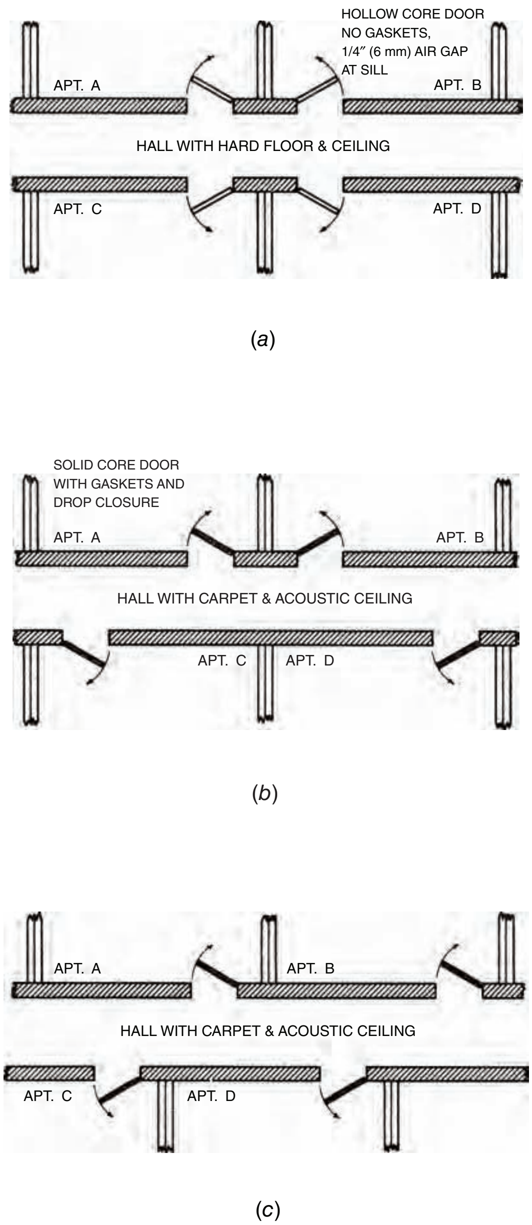
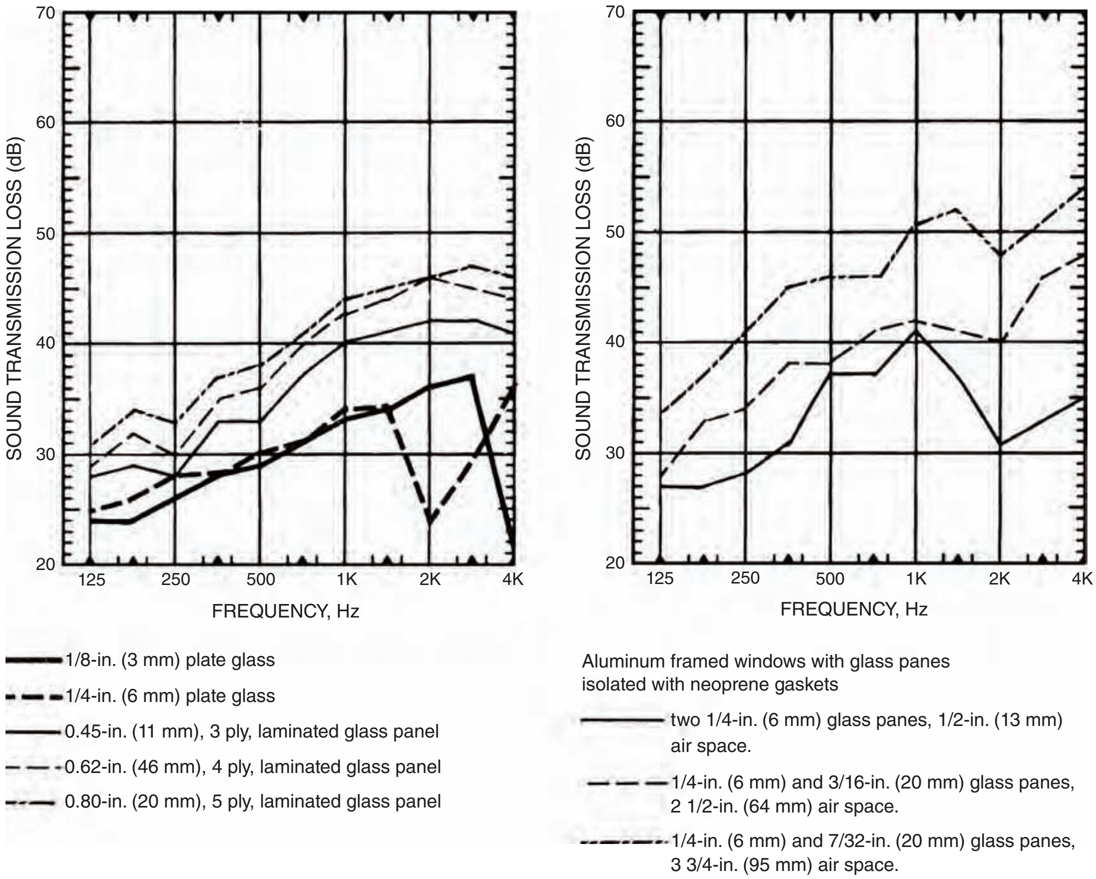
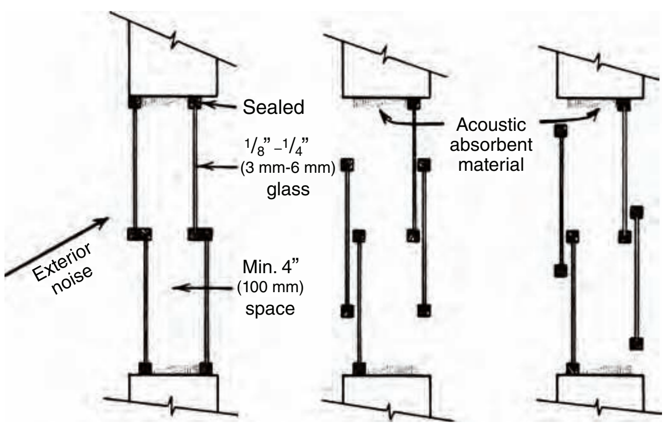


Fig. 24.26 *Proper arrangement of doors to rooms on a common corridor can diminish noise transfer in the area. (a) Poor arrangement because any noise emanating from one of the rooms or from the corridor has a very short and unattenuated path into the remaining rooms. (b) Better arrangement than plan (a) because noise from any source must travel a minimum of a room width along an absorbent corridor to reach any other room. Noise to the remaining rooms is further attenuated. The weak point of this plan is a noise short circuit via adjacent doors for Apt. A and Apt. B. Plan (c) is best because there are no short circuits for sound travel. Although the A–C and B–D paths are slightly shorter than in plan (b), the difference would not be noticeable. (Extracted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*



(*a*) (*b*)

Fig. 24.27 *(a) Sound transmission loss frequency spectrum shows the effect of thickening glass. The ¼-in. (6-mm) plate shows a very sharp (10-dB) coincidence dip at 2 kHz, making it less effective than a ⅛-in. (3-mm) plate between 1500 Hz and 2500 Hz. Further thickening with laminated glass eliminates the coincidence drop but reaches a practical limit at about ½-in. (13-mm) thickness. (b) Note that two ¼-in. (6-mm) panes with a ½-in. (13-mm) air space act as a stiff, thick pane and exhibit the sharp coincidence drop at 2 kHz. Larger sealed inter-pane air spaces markedly improve the acoustic insulation performance.*



TL = 35-40 dB (*a*)

10-20 dB (*b*)

15-25 dB (*c*)

Fig. 24.28 *The degree of attenuation of external noise can be regulated with acoustic sealant and absorbent materials when using pairs of double-hung (consider this a section view) or horizontally sliding (consider this a plan view) windows. Ventilation airflow varies inversely with transmission loss.*

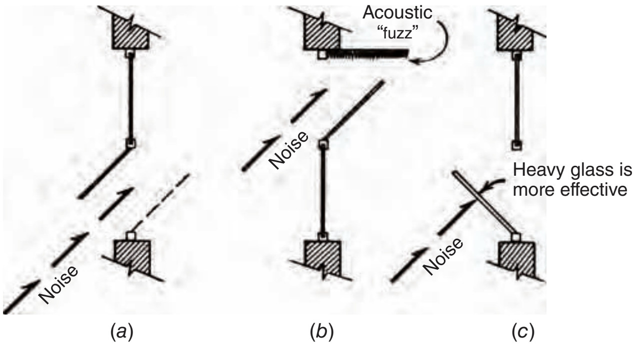


Fig. 24.29 *Alternative arrangements of the same basic "hopper" window design can yield results differing by as much as 10 dB. Design (a) is entirely open, and the noise path is unobstructed deep into the room. Design (b) is about 5 dB better than (a) at frequencies above 1 kHz because of higher absorption and less diffraction. Lower frequencies diffract readily around the window leaf and are less affected by absorptive material. Design (c) can be 10 dB better than (a), particularly at high frequencies, because it interposes a rigid barrier into the noise path. In this arrangement, the glass thickness is important.*

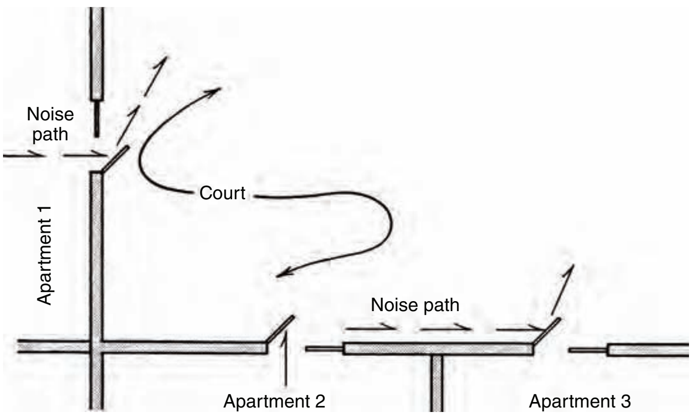


Fig. 24.30 *Noise transfer between contiguous corner spaces, as in Apartments 1 and 2, can be particularly severe if windows are improperly designed. Swinging windows, as shown, are preferable to double-hung or hopper windows because they reflect sound away from the adjacent space. Similarly, adjacent spaces on the same wall, such as Apartments 2 and 3, can benefit from this type of swinging arrangement, which is preferable to sliding or double-hung designs.*

are undesirable. Window-opening style and placement can also have an effect on the amount of exterior noise admitted, as shown in Figs. 24.29 and 24.30. Typical STC ratings of common window constructions are given in Table 24.4.

TABLE 24.4 Typical STC Values for Windows

Window Construction	STC
Operable wood sash, ⅛-in. (3.2-mm) glass, unsealed	23
Operable wood sash, ¼-in. (6.4-mm) glass, unsealed	25
Operable wood sash, ¼-in. (6.4-mm) glass, gasketed	30
Operable wood sash, laminated glass, unsealed	28
Operable wood sash, double-glazed, ⅛-in. (3.2-mm) panes, ⅜-in. (9.5-mm) air space, gasketed	29
Fixed sash, double ⅛-in. (3.2-mm) panes, 3-in. (76-mm) air space, gasketed	44
Fixed sash, double ⅛-in. (3.2-mm) panes, 4-in. (102-mm) air space, gasketed	48

24.14 DIFFRACTION: BARRIERS

The physical process by which sound passes around obstructions and through very small openings is called *diffraction*. Simply stated, diffraction is a process whereby any point on a sound wave establishes a new wave when passing an obstacle. Thus, although much of a sound wave is blocked by a small opening, the portion that does get through establishes a new wave front (see Fig. 24.18*e*). The *amplitude* of the diffracted wave is determined by the relationship between the size of the opening and the wavelengths of the signal components. For a small hole, short wavelengths (high frequencies) are attenuated less than long wavelengths (low frequencies). See Fig. 24.31.

When sound encounters a finite-length barrier, it diffracts around and over it, approximately as shown in Fig. 24.32. The attenuation of the

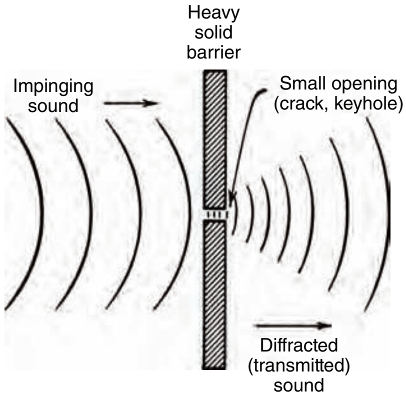


Fig. 24.31 *Sound passes through small openings by diffraction. The intensity of the transmitted sound is proportional both to its frequency and to the size of the opening. It is always less than the intensity of the impinging sound.*

diffracted sound depends upon the frequency, type of source, and dimensions of the barrier. For a *point source*, with only a single *practical* path around the obstruction (barrier), the noise reduction in decibels can be calculated from Maekawa's empirical equation (in I-P units):

$$NR = 20\log\left[\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}}\right] + 5\ \text{dB} \qquad (24.4)$$

where

$N = (f/565)\,(A + B - d)$
NR = noise reduction, dB
f = frequency, Hz
$A + B$ = shortest path length around the barrier, ft (over or around)
d = straight-line distance, source-to-receiver, ft

Note that this equation:

1. Is applicable only to exterior barriers where sound passing over the barrier is partially diffracted and partially attenuated by distance. In an interior situation, sound passing over a partial-height barrier (see Fig. 24.40) strikes the ceiling and is reflected down, increasing the received sound and effectively reducing barrier attenuation. Maximum exterior barrier attenuation is 24 dB, as

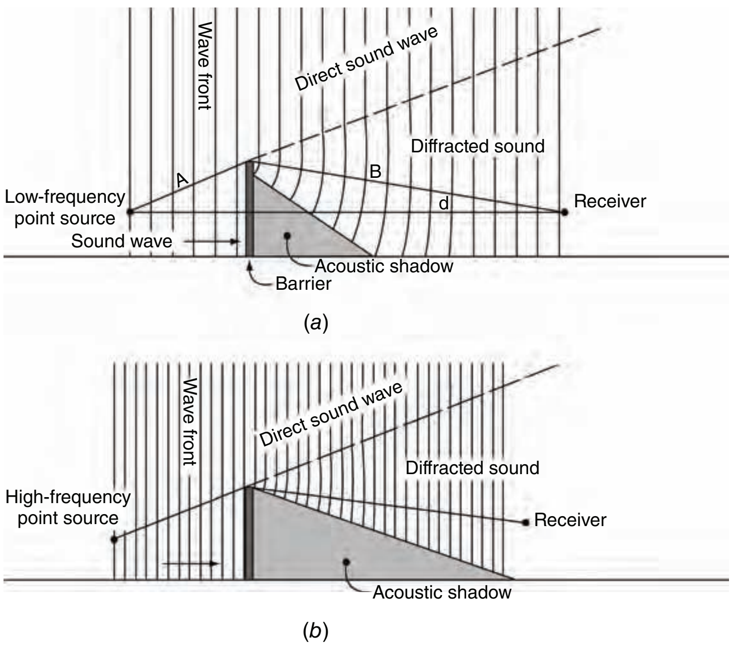


Fig. 24.32 *Comparison of the effect of a barrier on sources of different frequencies. The low-frequency sound (a) diffracts more readily over the barrier than the high-frequency sound (b) because of its longer wavelength. Thus, the lower the frequency, the smaller the acoustic shadow and the lower the barrier attenuation. The shadow is not as sharply defined as shown; it represents increasing attenuation closer to the barrier.*

compared to about 15 dB for a partial-height interior partition.

2. Assumes that the barrier is very long (or very high), so that only one sound path exists. In practice, a barrier whose length (height) is at least four times the distance between the source and the wall is sufficient if *the barrier is close to the source*. If the barrier is close to the receiver, it must be longer (higher) still.

3. Assumes a point source. Line sources (such as traffic) show 20 to 25% less attenuation for the same barrier.

The equation will, however, give reliable, usable results when the dimensions of the source are small with respect to the barrier, as is the case for:

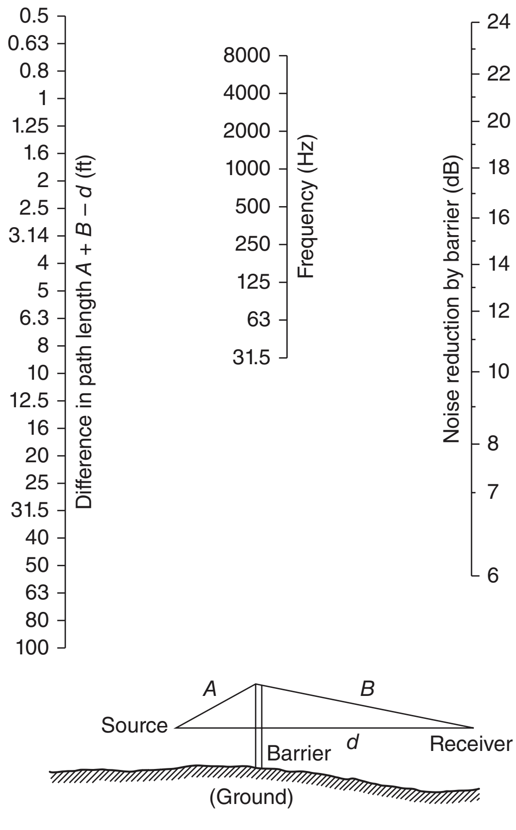


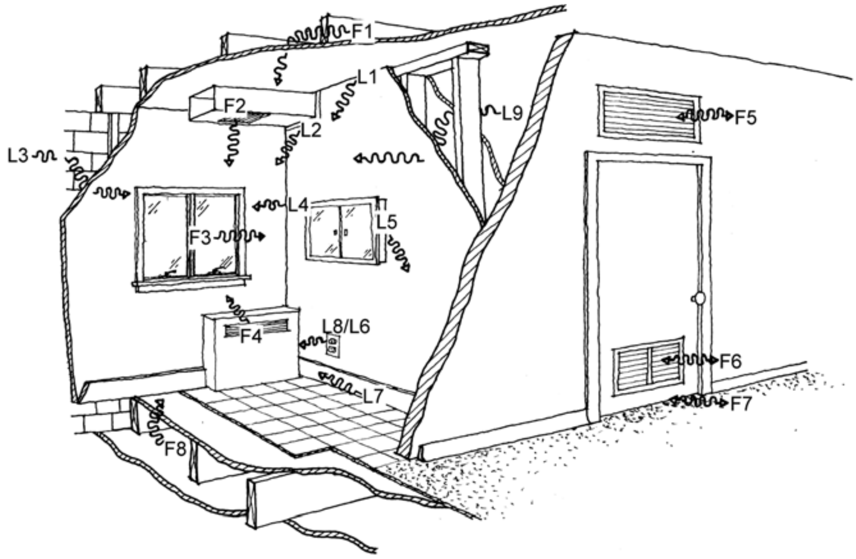
Fig. 24.33 *This nomograph for estimating the noise reduction afforded by a barrier is based on Equation 24.4 and assumes a point (small) source and only a single path around the barrier. The dimensions* A, B, *and* d *are taken from the insert sketch. Dimensions* A *plus* B *represent the shortest path around the barrier—which may be over or around it. (Reprinted with permission from B. Fader. 1981.* Industrial Noise Control. *John Wiley & Sons. Hoboken, NJ.)*

speech; individual motors, fans, engines, and other mechanical devices; and individual motor vehicles. The chart in Fig. 3.23 relates barrier dimensions and position to traffic noise reduction. Note that frequency is not a variable on the chart, since it has been plotted for an average attenuation at 220 Hz, which is the center frequency for random car and truck traffic.

It should be apparent that the best location for a barrier is either very close to the source or very close to the receiver. The worst position for attenuation is halfway between them. All effective barriers are assumed to be opaque and to have a minimum surface density of 5 lb/ft^2 (~25 kg/m^2). The inherent transmission loss of the barrier need not be very high; a massively thick barrier has only marginally higher attenuation than one with the aforementioned minimum surface weight. Absorptive material placed on the source side of a barrier will reduce the noise reflected back toward the source but will not effectively increase the barrier's attenuation with respect to the receiver. Although the maximum theoretical noise reduction of an *exterior* barrier is about 24 dB, in practice it rarely exceeds 20 dB. Figure 24.33 is a nomograph based upon Equation 24.4.

24.15 FLANKING

Just as sound will pass through the acoustically weakest part of a composite wall, it will also find parallel or flanking paths, that is, an acoustic short circuit. Proper design of window locations to avoid flanking paths has already been shown in Fig. 24.30. The same situation pertains with respect to doors, as shown in Fig. 24.26, and any other openings between spaces. Thus, in Fig. 24.34, a high-STC wall between the two spaces is in large measure defeated by flanking paths F5, F6, and F7. In other spaces the most common flanking path is via the plenum, as in Fig. 24.34 (path F1) and in Figs. 24.35*b* and 24.35*d*. Ductwork (with registers or grilles in various rooms) acts as an excellent intercom system unless it is completely lined with sound-absorptive material (see Section 24.27). Even then, low-frequency sound is only minimally attenuated, and special measures must be employed if good transmission loss is required. This subject is discussed further in Sections 24.25–24.27.



FLANKING NOISE PATHS

F1 OPEN PLENUMS OVER WALLS, FALSE CEILINGS
F2 UNBAFFLED DUCT RUNS
F3 OUTDOOR PATH, WINDOW TO WINDOW
F4 CONTINUOUS UNBAFFLED INDUCTOR UNITS
F5 HALL PATH, OPEN VENTS
F6 HALL PATH, LOUVERED DOORS
F7 HALL PATH, OPENINGS UNDER DOORS
F8 OPEN TROUGHS IN FLOOR-CEILING STRUCTURE

NOISE LEAKS

L1 POOR SEAL AT CEILING EDGES
L2 POOR SEAL AROUND DUCT PENETRATIONS
L3 POOR MORTAR JOINTS, POROUS MASONRY BLK
L4 POOR SEAL AT SIDEWALL, FILLER PANEL, ETC.
L5 BACK-TO-BACK CABINETS, POOR WORKMANSHIP
L6 HOLES, GAPS AT WALL PENETRATION
L7 POOR SEAL AT FLOOR EDGES
L8 BACK-TO-BACK ELECTRICAL OUTLETS

OTHER POINTS TO CONSIDER, RE: LEAKS ARE (A) BATTEN STRIP A/O POST CONNECTIONS OF PREFABRICATED WALLS, (B) UNDER-FLOOR PIPE OR SERVICE CHASES, (C) RECESSED, SPANNING LIGHT FIXTURES, (D) CEILING & FLOOR COVER PLATES OF MOVABLE WALLS, (E) UNSUPPORTED A/O UNBACKED WALL BOARD JOINTS, (F) EDGES & BACKING OF BUILT-IN CABINETS & APPLIANCES, (G) PREFABRICATED, HOLLOW METAL EXTERIOR CURTAIN WALLS.

Fig. 24.34 *Flanking transmission of airborne noise. (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD, 1968. Redrawn by Jonathan Meendering.)*

SPEECH PRIVACY

24.16 PRINCIPLES OF SPEECH PRIVACY BETWEEN ENCLOSED SPACES

The subject of speech privacy has always been of paramount importance in office design. Numerous studies have demonstrated that productivity and noise are related inversely when the noise carries information. When noise does not carry information, it can be annoying and therefore counterproductive or it can be useful as a masking sound, depending upon its frequency content, intensity level, and constancy. Referring to Section 24.7, which discusses the noise reduction of an *airtight* barrier between two spaces, we saw that the sound intensity levels in the source room (1) and the receiving room (2) are related by the expression

$$IL_2 = IL_1 - NR$$

where NR is noise reduction, and IL_2 and IL_1 are sound intensity levels in the receiving and source rooms, respectively. If the receiving room

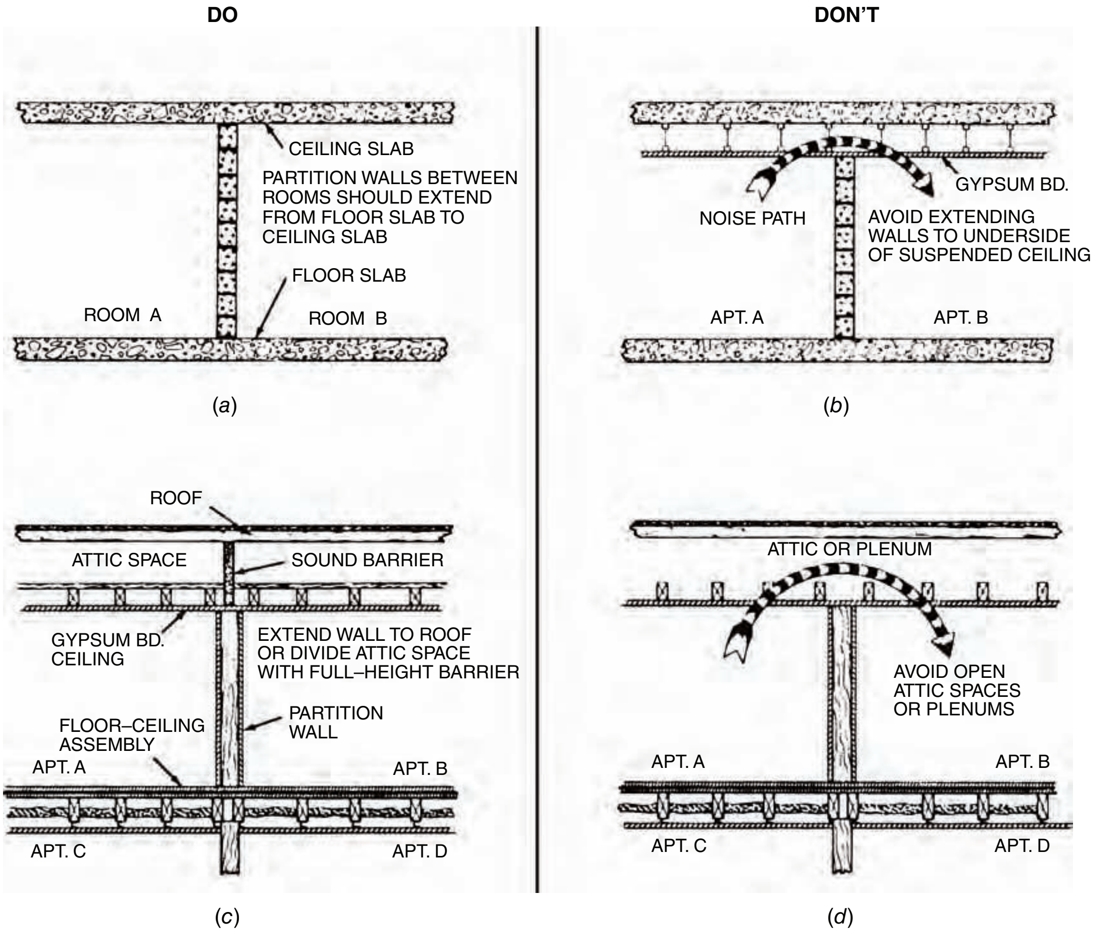


Fig. 24.35 *Construction technique recommendations to avoid flanking paths. (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*

is completely quiet and has no sound source other than the transmitted sound (essentially IL_2), then that sound will always be a potential source of annoyance to the occupant of the receiving room, as long as its intensity level is above the hearing threshold. If, however, there is a *constant* ambient sound level in the receiving room, then, depending upon its characteristics, it may mask the transmitted sound IL_2, even to the extent of making it completely inaudible. In most instances, however, it simply reduces or eliminates annoyance without completely masking the source. What we hear (and therefore what can potentially be a source of disturbance) depends upon our level of attention both to what we are doing and to the intrusive sound. (A remarkable exception is the ability of some, generally young, students to study in the presence of very loud, familiar—and therefore information-bearing—music. Indeed, some claim that they can *only* study that way.)

Tests have shown that a majority of adults will not consider an intruding noise level IL_2 to be annoying if the intensity of a properly designed background sound is either greater than or no more than 2 dB less than IL_2. Thus, a transmitted IL_2 of 40 dBA will not be considered annoying by most people if the level of the background sound is at least 38 dBA. The upper level of usable background masking sound is usually taken to be about 50 dBA. Any higher intensity level will itself become a source of annoyance. Figure 24.36 gives a graphic representation of the relation between transmitted

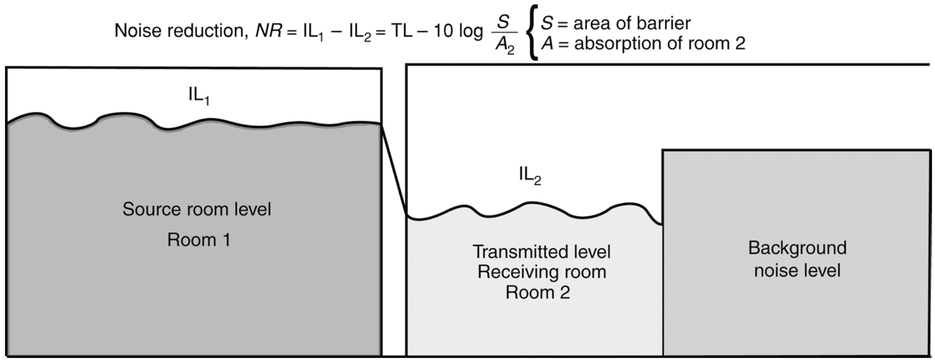


Fig. 24.36 *The background noise level determines whether a transmitted sound will actually be heard. In this case, because the background noise level is considerably higher than the transmitted level from the adjacent room, the transmitted noise will not be noticeable (i.e., it will be masked).*

and background sound levels in a receiving room. By way of summarizing the preceding discussion, we can simply state that the degree of *speech privacy* in a space is a function of two factors:

- The degree of sound isolation provided by the barriers between rooms
- The ambient sound level in the receiving room

24.17 SOUND ISOLATION DESCRIPTORS

Since the degree of intrusiveness of extraneous noise in a space varies, depending as it does upon both transmitted and ambient sound, having a descriptive scale of some sort is appropriate. If we restrict our discussion to speech sounds, since often we are interested in office design, where speech is the primary sound source, then a descriptive scale, as shown in Table 24.5, can be established. With these absolute descriptions in mind, and remembering that the hearing condition in a receiving room can be altered by changing either the barrier characteristics or the background sound level, *or both*, we can express the effectiveness of a construction as a speech-sound barrier in terms of its STC for a given ambient sound level. Since the ambient sound (noise) level is frequency dependent, it can be approximated by an NC value. This is particularly useful when the ambient sound level is generated by machinery or by the sound of an air-conditioning system rather than by a shaped signal from an electronic masking sound system.

Table 24.6 shows the hearing conditions in a receiving room with an NC-25 background noise as a function of the barrier STC rating. If the background noise level were raised to NC-30, then each descriptor would roughly increase one level in quality (i.e., poor would become fair, fair would become good, and so forth). Stated otherwise, the *apparent* isolation provided by a barrier may be increased by

TABLE 24.5 Relative Quality of Sound Isolation

Ranking	Descriptor	Hearing Condition[a]
6	Total privacy	Shouting barely audible.
5	Excellent	Normal voice levels not audible. Raised voices barely audible but not intelligible.
4	Very good	Normal voice levels barely audible. Raised voices audible but largely unintelligible.
3	Good	Normal voice levels audible but generally unintelligible. Raised voices partially intelligible.
2	Fair	Normal voice levels audible and intelligible some of the time. Raised voices generally intelligible.
1	Poor	Normal voice audible and intelligible most of the time.
0	None	Normal voice levels always intelligible.

[a]Hearing condition in the presence of ambient noise, if any.

TABLE 24.6 Relation between Barrier STC and Hearing Condition on the Receiving Side, Background Noise Level at NC-25

Barrier STC	Hearing Condition	Descriptor and Ranking[a]	Application
25	Normal speech can be understood quite easily and distinctly through the wall.	Poor/1	Space divider
30	Loud speech can be understood fairly well. Normal speech can be heard but not easily understood.	Fair/2	Room divider where concentration is not essential
35	Loud speech can be heard but is not easily intelligible. Normal speech can be heard only faintly, if at all.	Very Good/4	Suitable for offices next to quiet spaces
42–45	Loud speech can be faintly heard but not understood. Normal speech is inaudible.	Excellent/5	For dividing noisy and quiet areas; party wall between apartments
46–50	Very loud sounds (such as loud singing, brass musical instruments, or a radio at full volume) can be heard only faintly or not at all.	Total Privacy/6	Music room, practice room, sound studio, bedrooms adjacent to noisy areas

[a]See Table 24.5.

raising the background (masking) sound level in the receiving room. Figure 24.37 shows two conditions of adjacent spaces. Although the source room level is uniform and partitions on both sides of the source room are identical, the background sound in the two receiving rooms is different. In room A, the background is NC-35; in room B, it is NC-25. The occupant of room A is not disturbed by the little heard from the source room. The occupant of room B hears clearly. Occupant A will probably praise the partition, whereas occupant B will complain. Although the levels of reradiated sound are identical in the two receiving rooms, the intruding signal is masked by the background sound in A, but it is clearly audible in B. Thus, the apparent noise reduction is substantially higher in A than in B. This clearly demonstrates the effectiveness of masking sound in providing *apparent* sound isolation and speech privacy.

Sound isolation can also be improved by careful planning. Storage and circulation areas can serve as buffers for noise-sensitive areas. Physical separation of noisy areas from quiet ones often eliminates the need for complicated and expensive compound barriers.

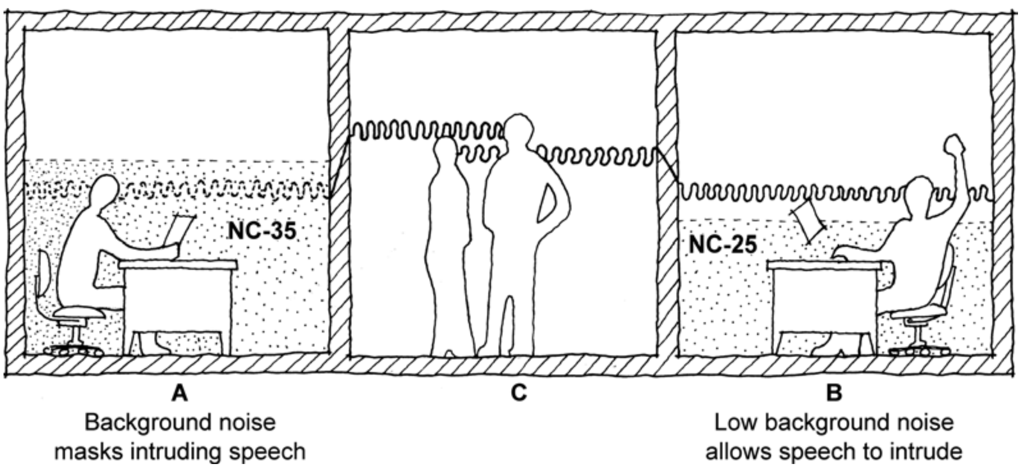


Fig. 24.37 *The occupant in room A with background noise NC-35 (≈ 45 dBA) is unaware of the noise (loud speech from room C) that is so disturbing to occupant B, whose NC-25 (≈ 36 dBA) is insufficient to mask the transmitted noise. (Drawing by Jonathan Meendering.)*

24.18 SPEECH PRIVACY DESIGN FOR ENCLOSED SPACES

The study of speech privacy received considerable emphasis with the advent of open-plan offices (office landscaping), although the same issues prevail with both open and enclosed office designs. Essentially, the problem was to determine the factors affecting speech privacy and to quantify them with a degree of accuracy sufficient for design purposes. It rapidly became evident that although the physical principles are the same, the solutions to speech privacy design problems are radically different for closed spaces and for open-plan offices. In the former, the acoustic character of an airtight barrier between two spaces is the crucial element in the design, because all of the interspace sound transmission is through this barrier. In contrast, sound transmission between adjacent "cubicles" in an open office is primarily the result of *reflected* and *refracted* sound, with the direct component passing through the barrier being of secondary importance. As a result, the acoustic transmission characteristics of the barrier also become secondary in importance.

Studies indicate that six factors are involved in enclosed-space speech privacy, which can be subsumed under two headings (Fig. 24.38):

1. Speech rating of the source room (Room No. 1)
   a. Speech effort. A measure of the loudness of speech.
   b. Source room factor. Gives the approximate effect of room absorption on the speech level in the source room. The scale in Fig. 24.38 is drawn for average absorption. For live rooms, raise the factor by 2 points; for dead rooms, lower it by 2 points. Factors $a + b$ give the approximate source-room voice level.
   c. Privacy allowance. What is the measure of privacy required?

The privacy criteria definitions used in this step (Fig. 24.38, Step 3) are:

Normal privacy. Such that the receiving-room occupant can understand a small portion of normal voice conversation in the source room by listening intently. This corresponds to "Good" and a ranking of 3 in Table 24.5. It was found that most occupants can work normally with this level of speech intrusion.

Confidential privacy. Assumes that only a few words will occasionally be intelligible. This privacy level corresponds to "Excellent" and a ranking of 5 in Table 24.5. The six speech-rating points between Normal Privacy (9 points) and Confidential (15 points) in Fig. 24.38 correspond roughly to a 5-dB difference. If we remember that a sound intensity differential of 3 dB is barely perceptible, 6 dB is clearly noticeable, and 10 dB is a doubling of perceived sound (Table 22.3), we can appreciate that the difference between *normal* and *confidential* privacy is small and calls for accurate design, plus a measure of field adjustment of masking sound.

2. Isolation rating of the receiving room (Room No. 2)
   d. The STC rating of the barrier. Table 24.7 gives some typical STC ratings for office partitions.
   e. The noise reduction factor A_2/S is an indication of receiving-room absorption, that is, the difference between *NR* and *TL*, where A_2 is the area of the receiving room, and S is the area of the barrier between the rooms. Absorption is assumed to be average. For live rooms, lower this factor 2 points; for dead rooms, raise it 2 points.
   f. For the recommended background noise level in the receiving room, use Table 24.8.

An analysis sheet for enclosed spaces is provided in Fig. 24.38 (see also Cavanaugh et al., 1962, and Young, 1965). The two examples of this analysis that follow should clarify its use. The reader should follow the analysis with Fig. 24.38 in hand. The numbered steps in the examples correspond to the numbers in the figure.

EXAMPLE 24.3 Evaluate the effectiveness of a proposed office partition.

Source room:
General clerical office, 40 ft × 60 ft × 9 ft (12.2 m × 18.3 m × 2.7 m), higher-than-average $\bar{\alpha}$, 16-ft (4.9-m) long full-height partition, STC 40

Receiving room:
Conference room, 16 ft × 24 ft (4.9 m × 7.3 m), medium-dead room
Background noise level, 40 dBA (NC-30) (from Table 24.8)

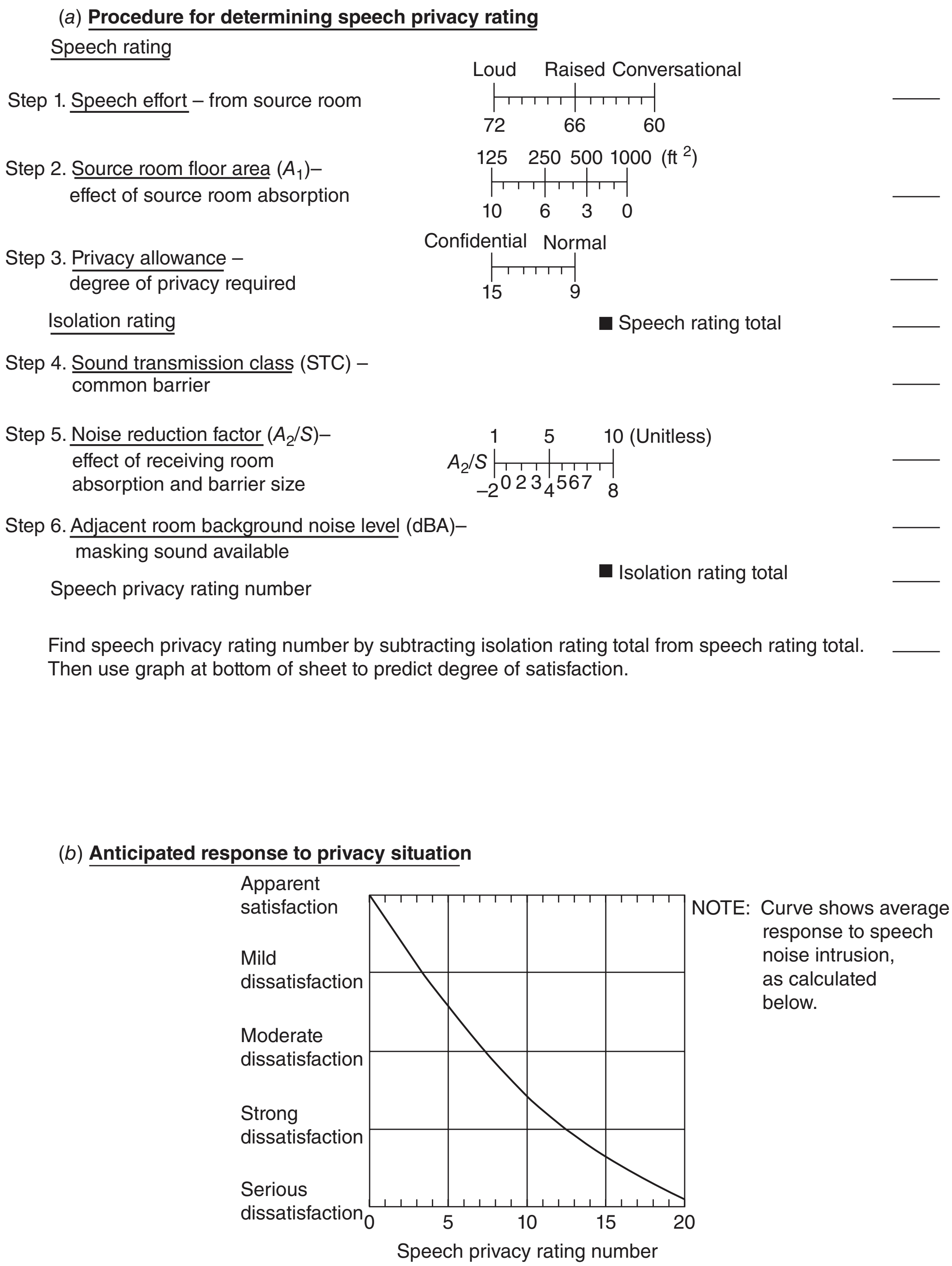


Fig. 24.38 *Speech privacy analysis sheet. (Based on Cavanaugh et al., 1962.)*

TABLE 24.7 Typical STC Ratings of Interior Partitions

Type of Partition	STC
Demountable partition	STC 20–30
Drywall partition up to acoustical ceiling	STC 30
Drywall partition extending 12 in. (305 mm) above acoustical ceiling tile system into ceiling plenum	STC 35
Drywall partition with cavity insulation, full height to the underside of slab above	STC 40–45
Two-layer drywall partition with insulation, erected full height to underside of slab above	STC 50

Privacy analysis (using I-P units as per Fig. 24.38):

(a) 1. Speech effort: raised 66
2. Area $A_1 > 1000$ ft^2 0
3. Privacy—normal 9
Speech rating a = 75

(b) 4. STC (given) 40
5. A_2/S 3
(16 × 24)/(16 × 9) = 2.6, corresponding to 2 on the scale; add 1 for higher than average $\bar{\alpha}$
6. Background noise level 40
Isolation rating b = 83
Speech privacy rating $a - b = -8$

The partition performance is acceptable. In fact, the STC rating of the partition could be reduced to 32 without affecting speech privacy. ■

EXAMPLE 24.4 Evaluate speech privacy.

Source room:
Design studio 20 ft × 30 ft (6.1 m × 9.1 m), medium-live
Common wall 12 ft × 8 ft (3.7 m × 2.4 m) high
STC: 26 (half glass, with door)

Receiving room:
Supervisor's office, 12 ft × 14 ft × 8 ft (3.7 m × 4.3 m × 2.4 m), average absorption
Background noise level, 35 dBA

Privacy analysis (using I-P units as per Fig. 24.38):

1. Speech effort: conversation 60
2. Source room factor:
For area +2
For liveness +1 Total +3
3. Privacy—(almost) confidential 13
Speech rating a = 76
4. STC (given) 26
5. A_2/S
(12 × 14)/(12 × 8) = 1.8, corresponding to a reduction factor of 1.6; gives 2.0 on the scale since the method uses whole numbers only. No adder required for average absorption.
Therefore, 2 + 0 = 2
6. Background noise level 35
Isolation rating: b = 63
Speech privacy rating $a - b = 13$
which indicates strong dissatisfaction

TABLE 24.8 Suggested Noise Criteria Ranges for Steady Background Noise

Type of Space (and Acoustical Requirements)	NC Curve	Equivalent[a] dBA
Concert halls, opera houses, and recital halls (for listening to faint musical sounds).	10–20	20–30
Broadcast and recording studios (distant microphone pickup used).	15–20	25–30
Large auditoriums, large drama theatres, and houses of worship (for excellent listening conditions).	20–25	30–35
Broadcast, television, and recording studios (close microphone pickup only).	20–25	30–35
Small auditoriums, small theatres, small churches, music rehearsal rooms, large meeting and conference rooms (for good listening), or executive offices and conference rooms for 50 people (no amplification).	25–30	35–40
Bedrooms, sleeping quarters, hospitals, residences, apartments, hotels, motels, and so forth (for sleeping, resting, relaxing).	25–35	35–45
Private or semiprivate offices, small conference rooms, classrooms, libraries, and so forth (for good listening conditions).	30–35	40–45
Living rooms and similar spaces in dwellings (for conversing or listening to radio and TV).	35–45	45–55
Large offices, reception areas, retail shops and stores, cafeterias, restaurants, and so forth (for moderately good listening conditions).	35–50	45–60
Lobbies, laboratory work spaces, drafting and engineering rooms, general secretarial areas (for fair listening conditions).	40–45	50–55
Light maintenance shops, office and computer equipment rooms, kitchens, and laundries (for moderately fair listening conditions).	45–60	55–70
Shops, garages, power-plant control rooms, and so forth (for just acceptable speech and telephone communication). Levels above PNC-60 are not recommended for any office or communication situation.	—	—
For work spaces where speech or telephone communication is not required, but where there must be no risk of hearing damage.	—	—

Source: Extracted with permission from E. B. Magrab, *Environmental Noise Control*, John Wiley & Sons, Hoboken, NJ, 1975.

[a]For information only. These data are not part of the NC information and do not appear in the source.

The suggested corrections are to increase the wall STC to 36 by gasketing the door and to increase the background noise level in the receiving room to 40 dBA (NC-30). This would give a speech privacy rating of −2, as follows:

STC of barrier	36
A_2/S	2
Background noise	<u>40</u>
Isolation rating	78

Speech privacy rating = $a - b = 76 - 78 = -2$

This result should be satisfactory according to the chart in Fig. 24.38. ■

24.19 PRINCIPLES OF SPEECH PRIVACY IN OPEN-AREA OFFICES

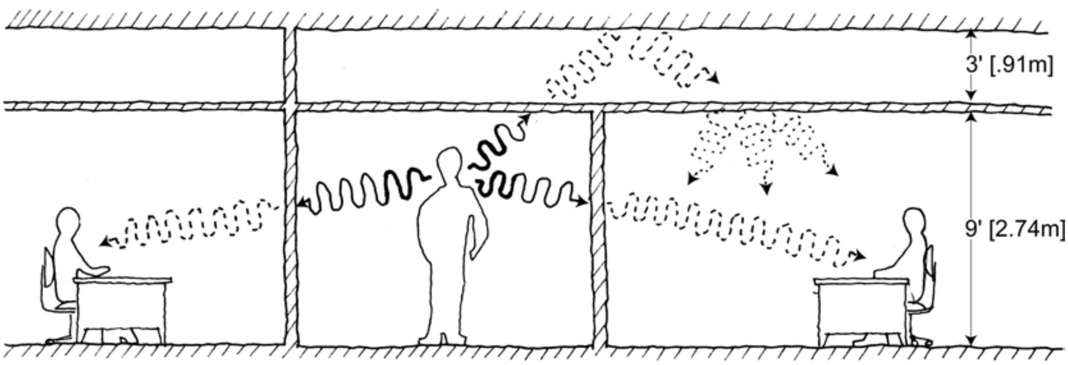
The huge increase in the service sectors of the world economy has brought with it a corresponding increase in desk jobs, each of which is often equipped with a computer console. This trend has also necessitated increased space density for office workers, made possible by the general elimination of paper storage (files) and the corresponding elimination of the necessity for employees to continually move about. The increased density problem has been largely solved by open-office plans with ever-smaller "cubicles," usually with single occupancy, but recently also with dual occupancy. This situation has aggravated the serious problem of annoyance due to the intrusion of speech sounds from neighboring workers, that is, a lack of *speech privacy*.

Since production is adversely affected by the inability of a worker to concentrate because of annoyance with speech intrusion—an annoyance that usually *increases* over time—the proper design of open office plans can have major economic benefits.

(a) Sound Paths in Open Offices

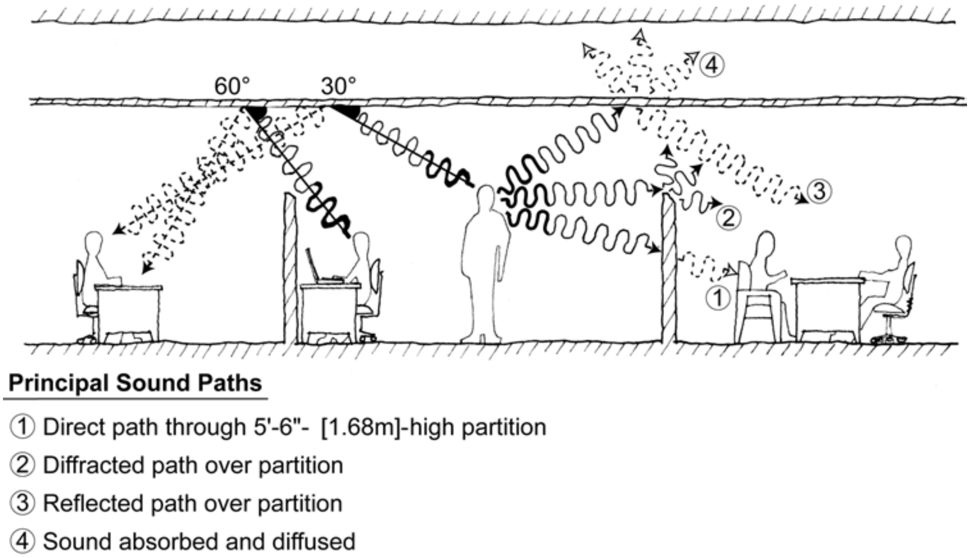
In contrast to the single, or at most dual, sound paths that exist with full-height enclosures (Fig. 24.39), the sound paths in an open-plan arrangement (including first reflections) are direct, diffracted, ceiling reflected, and laterally reflected (Figs. 24.40 and 24.41). Careful study of these illustrations shows a number of important facts affecting speech privacy in open offices.

1. The angles of reflection of sound waves from the ceiling depend upon the location and height of the source and the ceiling height (Fig. 24.40*a*). Measurements have shown that these angles vary from a minimum of 30° for a standing speaker in the center of a cubicle to a maximum of 60° for a speaker close to, and facing, a partition for ceiling heights of up to 9 ft (2.7 m). Since much of the sound energy reaching

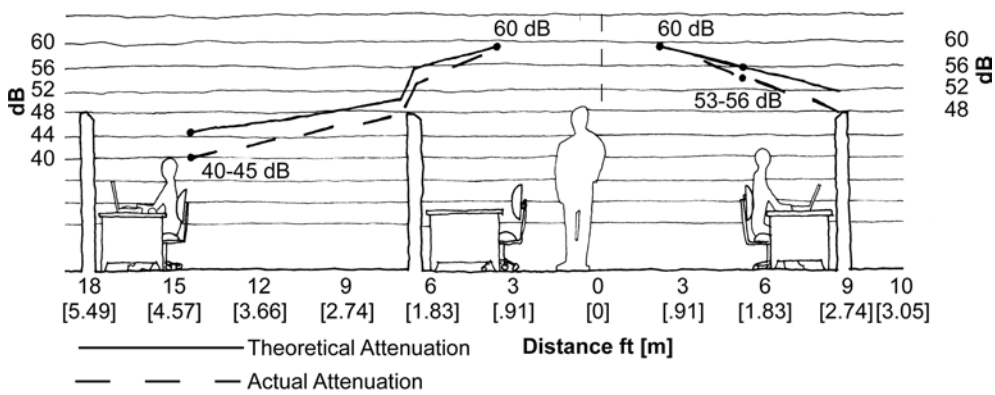


Interactive Animation

Fig. 24.39 *Sound paths between enclosed spaces are determined by the type of barrier separating them. In the case of a full-height barrier reaching to the underside of the ceiling slab, the only sound path is through the barrier, and its STC determines the sound pressure (noise) level in the receiving room. In the case of a ceiling-height partition with an overhead plenum, most of the sound energy will travel the upper, less attenuating path. Factors affecting the level of received sound are the ceiling's CAC rating (Ceiling Attenuation Class, indicative of its transmission characteristic) and the acoustic characteristics of the plenum, including all of its contents. In all cases, sound within a reasonably absorptive space attenuates with increasing distance. (Drawing by Jonathan Meendering.)*



(*a*)



(*b*)

Fig. 24.40 *(a) The principal sound paths between occupancies in an open office plan are (1) direct, (2) diffracted, (3) ceiling reflected, and (4) reflected from the slab above the plenum. Only paths (2) and (3) are problematic from the speech privacy viewpoint, requiring masking sound. Note that the angle of incidence of the sound wave at the ceiling varies from 30° for a standing speaker to 60° for a seated speaker, requiring a ceiling material of high absorption between these angles. Large VDT screens (17–19 in. [432–482 mm]), in common use, create another path of strongly reflected sound. (b) Sound is attenuated by distance, dropping 4–6 dB for each doubling of the distance from the source (6 dB in the open; 4 dB in enclosed spaces due to interreflections). Average SPL of conversational speech is 60 dBA at 3 ft (0.9 m) from a speaker. Attenuation of a diffracted signal at a partial-height partition is 4–8 dB. Note that the diffracted sound (without a contribution from ceiling-reflected sound) drops to 40–45 dB in the adjacent cubicle. In a two-person open office, the received signal from a standing speaker is at least 53–56 dBA (i.e., perfectly intelligible, even in the presence of maximum [50 dB] masking noise). (Drawings by Jonathan Meendering.)*

an adjacent occupant does so after reflecting off the ceiling at these angles (30°–60°), a ceiling material with high absorption at these angles of incidence is required for speech privacy. This effectively negates the use of the noise reduction coefficient (NRC) as a useful factor to describe a ceiling material's absorption characteristic in an open-office design, since the NRC averages absorption at all angles. All major ceiling material manufacturers have tested, and will supply, accurate angular absorption data for their products. A single-number descriptor that relates to

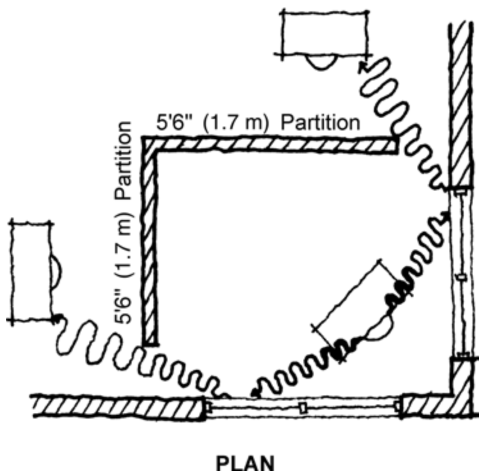


Fig. 24.41 *Confidentiality in offices on exterior building walls is difficult to maintain because of the lack of attenuation of sound reflected from windows. The problem is compounded by the custom of placing management personnel in such offices.*

this characteristic, called the *Articulation Class*, is discussed in detail in Section 24.20.

2. Since absorption at the ceiling increases with the angle of incidence of a sound wave, it is always desirable for speech privacy to have maximum ceiling height. Most authorities recommend a *minimum* ceiling height of 9 ft (2.7 m).

3. Absorption efficiency of ceiling tiles varies inversely with the STC, which is to be expected, since sound transmission depends upon mass and absorption at air pockets. Light fiberglass ceiling tiles will typically have an absorption coefficient α of 0.95 at voice frequencies, with a *Ceiling Attenuation Class* (CAC) of 22–24 compared to more massive mineral fiber tiles with a maximum α of 0.8–0.85 but an STC of 34–36. Since we are interested in maximum absorption at the ceiling, the tile of choice is always that with the highest α at voice frequencies. The fact that more energy will pass through a tile of lower CAC (STC) does not affect the acoustic result, since most of the sound energy enters the plenum above the ceiling through openings in the far-from-airtight suspension system, and is then largely absorbed and dissipated by the spray fireproofing, sound-absorbing material, ductwork, and structural members typically found in a plenum.

4. Since sound will always find the path of least resistance to travel, very little sound energy will pass through partitions between cubicles; the paths over the partition by diffraction and reflection are much less resistant. That being so, the STC of these partitions need not be high. Where the source is close to the partition, as is the case with a seated speaker facing a partition and delivering sound energy directly at the partition at a height of approximately 44–48 in. (1.1–1.2 m) from a distance of about 3 ft (0.9 m), the STC of the partition should be 25–26. For speakers at greater distances and heights, an STC of 20–22 is usually sufficient.

An exception to this general rule *may* occur when a large (17 to 19 in. [430 to 480 mm]) computer display is interposed between a seated speaker and an absorbent partition. If such digital screens are composed of a smooth, highly reflective glass surface, a strong sound path to the rear of the speaker is created, and the sound energy absorbed by the partition behind the digital screen is decreased. The variables, however, are so numerous that conservative design will use the higher STC rating. (Contrast these values with those required of a full-height, fixed-partition construction typical of enclosed spaces, as listed in Table 24.7.)

The absorption coefficient α of a partial-height partition at voice frequencies should be a minimum of 0.8 and preferably 0.85–0.95. Some manufacturers have assigned an Articulation Class rating to their partition products, although that descriptor is usually reserved for ceiling tiles, as explained in point 3. The recommended ratings for partitions range from 180 to 220.

5. Partitions must be tall enough to block direct line-of-sight voice transmission, since such a path is unattenuated except by distance. The median mouth height of a standing American male is 63 in. (1.6 m). This is the basis of the widely accepted recommendation that partitions between adjoining cubicles should not be lower than 65 in. (1.7 m) and preferably 66–72 in. (1.7–1.8 m). Since a 72-in. (1.8 m) high partition blocks vision for all but the tallest people, giving a subjective closed-in sensation to the occupant of a (small) cubicle, this height is normally used only between departments, with intradepartment partitions being 63–66 in. (1.6–1.7 m) high. Increasing the height of a partition from 65 to 72 in. (from 1.7 to 1.8 m) will increase path attenuation to an adjacent cubicle by 1–3 dB, depending upon ceiling height and speaker height and location.

6. Refer to Fig. 24.40*b*. This figure indicates signal attenuation due to distance for two different paths. Speech intensity at a conversational level is approximately 60 dBA at 3 ft (0.9 m) from the speaker. Using the fact that sound in a free field attenuates 6 dB for every doubling of distance, and making the assumption that the sound field in a cubicle approaches that of a free field because of the large amount of highly absorptive material in the area, we obtain a sound intensity level of 54 dBA at 6 ft (1.8 m) from the speaker and 48 dBA at 12 ft (3.7 m). In practice, the received sound level is several decibels higher because, despite the high α of the space, there are intraspace reflections that increase the sound level.

Referring again to Fig. 24.40*b*, we see that the minimum sound level at a receiver *within* the cubicle would be 55–56 dB, a level that no practical amount of background sound can mask. Thus, two occupants of a single large cubicle will always hear each other quite clearly. The attenuation of a partition in the diffracted paths (over and around a partition) depends upon the location and height of the speaker and varies from 4 to 8 dB. The attenuation of the signal in the transmitted path (through the partition) will be at least 10 dB. Based on these figures, it is recommended that the *minimum* horizontal distance between occupants of adjoining cubicles when seated at their workstations be 10 ft (3 m) for minimum speech privacy. (Degrees of speech privacy are discussed in the next section.) Speech levels in teamwork areas readily reach 66 dB. This necessitates either locating such areas away from normal working spaces or the use of full-height fixed or demountable partitions to completely enclose such areas. The spaces that require careful siting or complete enclosure because of raised voice levels (64–66 dB) include videoconferencing rooms, telecommunications spaces, and areas where workers use speakerphones or voice-activated computers. The latter two devices are usually forbidden in densely populated work areas where a reasonable degree of speech privacy is required for the conduct of regular business tasks.

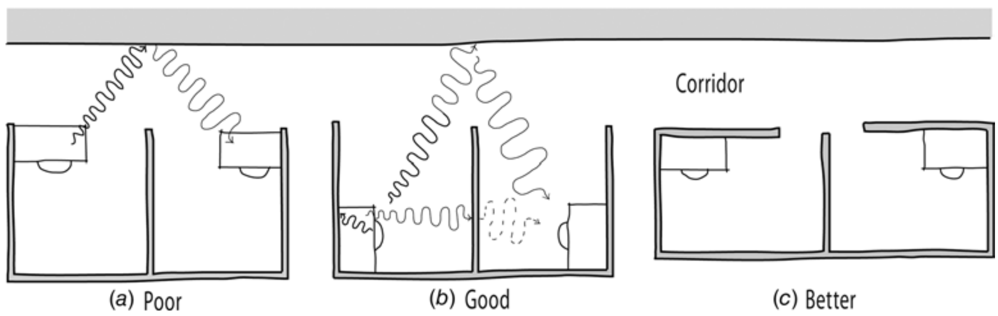
7. Refer to Fig. 24.41. As pointed out previously, sound will be received via paths of least resistance. These are often flanking paths that do not become evident except in plan view. In Figure 24.41, the flanking paths are particularly important because the first reflection occurs at a window. Glass has negligible absorption and, because of its smoothness, exhibits specular reflection. As a result, the corner office occupant's voice will be heard clearly via the flanking paths shown, thus destroying the confidentiality of conversation in that office. Since offices on the building perimeter are usually reserved for middle and upper management, and since the large windows in such offices act to minimize the speech privacy so important to managerial personnel, the space designer has several options to ameliorate this condition:

a. Use full-height fixed partitions, with fixed glass vision panels if required, and doors rather than openings.
b. Use heavy drapes over "offending" glass windows, although this option defeats the visual and daylighting purpose of the windows.
c. Group spaces requiring confidentiality together, using unoccupied areas such as storage rooms as sound-buffers from open-office spaces.

It is also important to note that although the arrow signifying a sound path in Fig. 24.41 shows reflection from the windows, the sound energy will also strike the exterior walls, which are usually plastered and therefore highly reflective. Here, the placement of absorbent acoustic material on all walls, to ceiling height, is not impractical, as it is with windows, but it does entail considerable expense.

8. Refer to Fig. 24.42. The furniture arrangement establishes the source location of speech energy and consequently all of the sound paths that contribute to speech privacy—or, more accurately, to the lack of speech privacy. In layout (*a*), sound power, unattenuated except by distance, reflects off the *back* of the opposing aisle partition and travels to the occupant of the neighboring cubicle. Since the back of an acoustic partition is usually metallic and nonabsorbent, this arrangement would entail the additional expense of an absorbent rear surface on the corridor panels to maintain a degree of speech privacy between cubicles.

Changing the desk location in the same-shaped cubicle to that shown in Fig. 24.42*b* improves speech privacy considerably by reducing the SPL of both the reflected and flanking paths, since the speakers face a highly absorptive surface. It may be unnecessary to use absorbent material on the rear of the corridor panels. A disadvantage of this arrangement lies in the short distance between



Interactive Animation

Fig. 24.42 *Open-office shapes and furniture arrangements have a marked effect on speech privacy. (a) A strong, unattenuated signal reflects from the opposite corridor wall directly into the adjoining office. The side-to-side 15-ft (4.6-m) total spacing with an intervening partition is barely satisfactory. (b) The sound reflected from the corridor wall is much weaker than in (a) because of increased distance and decreased voice intensity from the side. Lateral sound is also weak due to the attenuation at the first reflection off the absorbent partition. (c) Reflection from the corridor is eliminated by the use of a front closure partition with glass at the upper 18 in. (457 mm) for visual purposes. Side-to-side sound transfer is weak due to wide spacing and the intervening partition. (Drawing by Nathan Majeski.)*

speakers and neighbors if the same pattern of cubicles is continued longitudinally. A second possible disadvantage may be employee dissatisfaction with a working position facing a blank wall.

The arrangement in Fig. 24.42*c* uses the same area per cubicle. By changing its shape and adding a 6-ft-high (1.8 m) acoustic partition whose top 18 in. (457 mm) is glass, the designer has reduced the sound energy levels in all paths while overcoming any employee resentment related to working in a blank, unexposed corner. Furthermore, the problematic flanking path in Fig. 24.42*a* has been eliminated, as has probably any requirement for exterior acoustic absorption on the corridor partitions.

24.20 OPEN-OFFICE SPEECH PRIVACY LEVELS AND DESCRIPTORS

(a) Factors

The factors involved in determining the level of acoustic privacy that can be expected at a specific open-office location, as a result of neighboring speech sources, should be understood at this point. It may be helpful, however, to restate them. They are:

1. Loudness of the source(s).
2. Acoustic characteristics of the source(s). These include location, height above the floor, directivity, frequency spectrum, and information content. The last factor refers to the ability of a listener to make sense of what is being said or heard. Therefore, most types of non-information-bearing sound would not be considered intrusive sources of noise. A completely foreign language should also fall into this category, although in practice that is so only when the words and syllables are muffled. Clearly heard words in a foreign language do constitute a source of speech annoyance, although to a far lesser extent than those in a comprehended language. Speech privacy calculation procedures ignore foreign languages and assume that all speech is a possible source of annoyance.
3. Signal attenuation along each path between the source and the receiver. This factor is different for every normal position of even a single source, as, for instance, for a seated or standing source person.
4. Level and frequency content of background sound (deliberate masking, HVAC noise, continuous machinery noise, and the like).
5. Degree of privacy required. This is discussed in detail in the next subsection. It is important to keep in mind, however, that the three classifications—confidential, normal, and transitional (minimal, marginal)—are assumed to remain constant as long as the physical factors involved do not change. This ignores the oft-demonstrated fact that intrusive noise causes psychological and physiological reactions in some people that tend toward aggravation and that increase in severity with passage of time. A speech privacy situation originally classified as

confidential may deteriorate to normal as the hearer's increasing sensitivity to noise causes him or her to strain to hear, and thereby to actually hear sound that ordinarily is masked. This is, in effect, another aspect of the cocktail party effect discussed in Chapter 22.

(b) Levels (Degrees) of Speech Privacy

Speech privacy is often achieved by masking intruding speech with background sound. By consensus among acousticians, the definitions of the three levels of speech privacy in an open office are:

1. *Confidential privacy.* Normal voice levels are audible but generally unintelligible. Raised voices are partially intelligible. Noise level is minimal. To achieve this level of privacy, the background sound level must be no more than 2 dB less than the intruding sound, and no more than about 3 dB more than the intruding sound, to satisfy the minimal noise level requirement. In this acoustic situation, approximately 95% of people will not sense any sound-intrusive disturbance and will be able to concentrate on most types of work.

2. *Normal privacy.* At this level, normal voice levels from adjacent spaces are heard but are not intelligible without concentration (i.e., by straining to hear and catch every syllable). Raised voices are generally intelligible. The overall noise level is low. This level of speech privacy is achieved when the background sound level is within 6 dB of (less than) the intruding speech level. This corresponds roughly to an intruding speech level of 50 to 54 dB, and a background sound level of 44 to 45 dB, that together give a range of 51 to 55 dB, levels that can be considered to meet the low-noise requirement.

3. *Transitional (minimal, marginal) privacy.* At this speech privacy level, speech at normal voice levels in adjacent open offices is readily understood most of the time, and the overall noise level is average. This noise level occurs when the intruding speech level is at least 10 dB more than the background sound level. Since background sound is limited to about 50 dB, this privacy level would mean an intruding speech intensity of 60 dB or more. Since 60 dB is approximately normal speech at 3 ft (0.9 m), this "privacy" level would occur with two occupants in a single office or a single occupant receiving intruding noise from at least three neighboring offices. This speech intrusion level would be considered intolerable by about 40% of people and would negatively affect the work efficiency of a higher percentage.

In summary, it is interesting to compare these three open-office speech privacy levels with the "absolute" grading given in Table 24.5:

Open-Office Class	Table 24.5 Rating
Confidential	Good
Normal	Fair
Marginal	Poor

It should therefore be apparent that, by its very nature, an open office cannot achieve the top three grades of privacy listed in Table 24.5. If those levels of privacy are desired or required, fully enclosed spaces are necessary.

(c) Articulation Index (AI)

In order to quantify speech privacy for an open-office design, a single-number metric called the *Articulation Index* (AI) was developed in the 1970s by the acoustics consulting firm of Bolt, Beranek and Newman. This work was based in part upon studies of speech intelligibility by Bell Labs in the 1940s. Essentially, the AI relates speech intelligibility, speech intensity, and background sound level at the center of the five octave band frequencies that encompass the spectrum of the human voice: 250, 500, 1000, 2000, and 4000 Hz. AI is determined by measuring the percentage of individual words that can be understood under specific speech and background sound levels. An AI of 0% indicates zero intelligibility and therefore ideal speech privacy. This, of course, does not mean silence; it means that with a specific combination of speech intensity level and background sound level, intelligibility is nil, and therefore speech privacy—defined as a lack of intelligible intruding speech—is ideal. At the other end of the scale, a high percentage of intelligible words yields a high AI and a correspondingly low speech privacy rating. In practice, the resultant AI figures are related to listener satisfaction and speech privacy descriptors, as shown in Table 24.9.

The calculation procedure for AI involves the use of weighting factors that are applied to intensity-level differences between speech and background sound levels at different frequencies, in order to reflect the connection between intelligibility

TABLE 24.9 Articulation Index (AI) and Speech Privacy

AI	Persons Satisfied with Speech Privacy (%)	Open-Office Speech Privacy Descriptor
0–0.05	95–92%	Confidential
0.06–0.2	90–80%	Normal
0.21–0.3	79–65%	Minimal
>0.3	<65%	Unacceptable

and frequency. As pointed out in Chapter 22, most of the information in English words is carried by consonants, whose frequencies are generally above 2 kHz. Thus, the problem frequently encountered in telephone conversations, of distinguishing between *f* and *s*, *b* and *v*, *t* and *d*, and so on, is due to excessive attenuation of the high frequencies that distinguish these letters from each other. The AI calculation emphasizes the importance of high frequencies to intelligibility by using the following weighting factors:

Octave Band Center Frequency (Hz)	Relative Weighting Factor
250	1.0
500	2.5
1000	3.5
2000	5.0
4000	4.0

The calculation of AI values for an actual open-office design is complex and laborious, since it considers all sound paths between each source and each receiver, including the acoustic characteristics of all reflective and absorptive surfaces in the path. The results are a specific AI factor for every receiver location. Because of the very large number of calculations involved, the analysis is done by computer. Changes in materials, plan arrangements, and dimensions can be made if the calculated AI does not satisfy the space's speech privacy requirement.

These changes can be predicted fairly accurately, since it has been demonstrated that a 3-dB change in the relative level of an intruding speech signal with respect to the background sound level will result in a 0.1-level change in AI. Thus, an increase of 3 dB in the background sound level or a decrease of 3 dB in the intruding signal (by increased absorption or path length) will have the effect of increasing the AI between the involved workstations by 0.10, which is the difference between normal and poor speech privacy. Since 3 dB is a barely perceptible change in intensity (see Table 22.3), we can appreciate how sensitive speech privacy is to small changes in intensities.

(d) Articulation Class

Numerous measurements in actual open-office installations have indicated that the absorption characteristics of the ceiling are the most important factors in speech privacy design. As noted in the previous section, the angles of incidence of speech sound on the ceiling range between 30° and 60°, with the majority of sound energy falling at the top of this range. A figure of merit for absorption, called the *Articulation Class* (AC), was established that indicates absorption effectiveness at angles of incidence between 45° and 55°. The usual range of AC is between 180 and 220 (no units), with higher numbers representing better absorption.

24.21 DESIGN RECOMMENDATIONS FOR SPEECH PRIVACY IN OPEN OFFICES

(a) General Factors

The architectural arrangement of spaces in an open-office design has a marked influence on speech privacy. Areas should be grouped according to their speech privacy requirements. Spaces rated as "confidential" should be placed on the perimeter of the open area to limit their exposure to speech intrusion—with the caveats relating to exterior windows and walls, discussed previously, being considered. The design emphasis for these areas should be not only on an AI between 0.0 and 0.05, but also on a low overall sound level, *including* background noise. Similarly, high-noise-producing areas should be grouped and placed on the perimeter at a maximum distance from confidential speech privacy areas. Use of demountable full-height partitions for such spaces should be considered.

Because of reflection from perimeter walls, open-area spaces should be as large as practical, with absorbent perimeter walls. Ceiling height should be no less than 9 ft (2.7 m) clear, with a 3-ft (0.9-m) plenum above. Extreme care must be taken with air-conditioning ductwork, which, if untreated, will act as an excellent speech and noise conduit via multiple ceiling outlets. Furthermore, these outlets, which were once relied upon to produce an even level of background sound, generally no longer do so. Most HVAC systems today are variable air volume (VAV) designs, whose noise levels vary ±10 dB, making them useless as a reliable source of masking sound.

(b) Individual Office (Cubicle) Design

Offices should be designed for maximum closure and maximum partition length. Separation between occupants of adjacent offices should never drop below 10 ft (3 m), with a 12-ft (3.7-m) minimum as a design target for normal privacy and 16 ft (4.9 m) for confidential privacy. Minimum office area should be 80 ft^2 (7.4 m^2), with a design target of 100 to 120 ft^2 (9.3 to 11.1 m^2) for normal privacy and 200 ft^2 (18.6 m^2) for confidential privacy. Desk arrangements should be checked for optimum speech paths (for privacy), recognizing that office furniture arrangements need not be uniform in all offices (see Section 24.19).

(c) Ceilings

Because the ceiling is the most important design element in speech privacy, care must be taken to avoid unintentional strongly reflective speech paths, as from metal pan air diffusers, flat lighting fixture diffusers, and the like. If the use of such or similar items is unavoidable, highly absorptive vertical baffle strips may be placed on their perimeter to block sound paths. In general, ceiling tiles should have an Articulation Class rating of 220 minimum, and minimum absorption coefficients (α) at incidence angles of 30°–60° as follows:

Frequency (Hz)	α
250	0.65
500	0.65–0.75
1000	0.85
2000	0.90
4000	0.90

(d) Partitions

As explained in Subsection 24.19(a), the minimum height of partitions should be 65 in. (1.7 m), with 72-in. (1.8-m) high units separating offices from aisles and dividing departmental groups. The AC rating, if available, should range from 200 to 220. STC ratings, as explained in Section 24.11, depend to an extent upon speaker locations and vary from 20 to 26. Joints between partitions should be carefully sealed, because even small openings can seriously compromise a partition's already limited efficiency. All partitions should reach the floor, although the lower portion is not always absorptive in low-speech-privacy areas.

(e) Floors

Although carpeted floors do not seriously affect overall sound absorption, they do drastically reduce chair-movement and footfall sounds. For this reason, all floors in open office areas should be carpeted. The difference in effectiveness of shallow-pile carpet compared to deep-pile carpet is minimal, and the same differential can be achieved by using a polyurethane cushion backing in lieu of the more common jute pad. The principal purpose of carpeting is to cushion the footfall impact so that its energy is not introduced into the structure. This subject is covered in detail in the discussion of structure-borne sound that follows.

(f) Lighting Fixtures

Flat-bottom lighting fixtures must never be used. Fixtures should not be placed directly over partitions, in order to avoid an interoffice speech reflection path. Experience has shown that the best lighting fixture (from the speech privacy point of view) is one with deep parabolic reflector cells and overall dimensions of 1 ft × 4 ft (0.3 m × 1.2 m) or 2 ft × 4 ft (0.6 m × 1.2 m).

(g) Masking Sound

It is imperative that the level of masking sound be uniform throughout an open office area, and at as low a level as will yield the desired speech privacy. Nonuniformity will immediately be noticed as people move about, and the masking sound itself will become a source of auditory annoyance. For a similar reason, loudspeakers should not be visible. Visible units become themselves a source of interest initially and then a source of annoyance. Speakers should be placed *in* the plenum, preferably facing up to increase dispersion and improve uniformity. Speakers mounted in the ceiling and facing down should be avoided. Most ceiling tiles in open-office spaces have a low CAC so that sound will easily penetrate into the office area below the ceiling.

A masking sound system should comprise a signal (noise) generator, a sophisticated equalizer for shaping the signal, an amplifier with appropriate controls, and a distribution system to feed the speakers. Speakers are normally 12 in. (305 mm), and are installed in a grid on 12- to 16-in. (305 to 406 mm) centers. The amplifier should be arranged so that volume levels can be remotely controlled. This permits time control so that the background sound volume can be reduced automatically after working hours. This is necessary so that the few people working late are not annoyed by relatively loud background sound in the absence of intruding speech.

The noise produced by a masking sound system is variously described as white noise, noise of air rushing through an opening (whoosh sound), noise of water in piping, and the like. The actual sound can be tailored to the user's preference by adjusting the filters in the system's equalizer. Generally, masking sound emphasizes low frequencies, because higher frequencies are immediately noticed as an annoying hiss. As noted in Section 24.16, the background sound level should not exceed 48 to 50 dBA. In some installations, the masking sound system doubles as a public address system, although this practice is not recommended because the sound/noise stops during an announcement, and when it returns it is noticed. Background sound must be designed so as to blend into the ambience of the background, and anything that disturbs the hidden quality of masking sound is to be avoided.

(h) Design Procedure

Unfortunately, due to the large number of variables involved in open-office speech privacy design, a straightforward manual design method that will yield reliable results does not exist. However, a number of computer programs are available that will calculate the AI for any location as a result of a specified speech source intrusion. On the basis of these calculations, changes can be made to the design and the program rerun to achieve improvements where the calculated AI is excessive. The most effective way to perform a complete design is then, on the basis of the preceding calculations, to construct a full-scale mock-up that can be field-tested and "tuned." Although this is expensive and time-consuming, it is frequently far cheaper than making the requisite changes after construction of an unacceptable solution.

One of the distinct advantages of this two-step design procedure is that it enables a designer to equalize the acoustic absorption "strength" of various paths so that the attenuations of major paths are equal. There is no economic or engineering sense in a system that is much more effective for one path than for another, since sound will always follow the path of least acoustic resistance. To accomplish this balancing, the designer has many variables to juggle. They include barrier height and material, ceiling material, baffle sizes and positions (if used), distances between the source and receiver, position and directions of sources, and level of background sound.

(i) Standards

The acoustic design and testing of open offices is covered by a group of American Society for Testing and Materials (ASTM, see Section 24.37) standards that should be in the hands of anyone engaged in open-office design. The standards are available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM E1573-09, *Standard Test Method for Evaluating Masking Sound in Open Offices Using A-Weighted and One-Third Octave Band Sound Pressure Levels*. This test method specifies the procedures that can be used to evaluate the spatial and temporal uniformity of masking sound in open offices using A-weighted sound levels. It also specifies the procedure for evaluating the masking sound spectrum and level using ⅓-octave band sound pressure levels.

ASTM E1110-06(2011), *Standard Classification for Determination of Articulation Class*. This classification provides a single-figure rating that can be used for comparing building systems and subsystems for speech privacy purposes. Excluded from this classification are applications involving female speakers and children, languages other than English, and sound spectra other than speech.

ASTM E1111-07, *Standard Test Method for Measuring the Interzone Attenuation of Open Office Components*. This test method is intended to provide measurements of the speech privacy characteristics of ceiling systems (with partial-height partitions), furniture panels, and vertical panels.

ASTM E1130-08, *Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index*. This method describes a field test for measuring speech privacy objectively between locations in open plan spaces. It relies upon acoustical measurement, published information on speech levels, and standard methods for assessing speech communication. This test method does not measure the performance of individual open-plan components that affect speech privacy; it measures the privacy that results from a particular configuration of components. This method relies upon the AI, which predicts the intelligibility of speech for a group of talkers and listeners.

ASTM E1179-13, *Standard Specification for Sound Sources Used for Testing Open Office Components and Systems*. This specification states the requirements for sound sources used for measuring the speech privacy between open offices or for measuring the laboratory performance of acoustical components. The sound source is a loudspeaker located in an enclosure and driven with an appropriate test signal.

ASTM E1264-08e1, *Standard Classification for Acoustical Ceiling Products*. This classification covers ceiling products that provide acoustical performance and interior finish in buildings. It classifies acoustical ceilings by type, pattern, and certain ratings for acoustical performance, light reflectance, and fire safety.

ASTM E1374-06(2011), *Standard Guide for Open Office Acoustics and Applicable ASTM Standards*. This guide discusses the acoustical principles and interactions that affect the acoustical environment and acoustical privacy in an open office. In this context, it describes the application and use of the series of ASTM standards that apply to open offices.

ASTM E1375-90(2002), *Standard Test Method for Measuring the Interzone Attenuation of Furniture Panels Used as Acoustical Barriers*. This test method covered the measurement of the interzone attenuation of furniture panels used as acoustical barriers in open-plan spaces to provide speech privacy or sound isolation between working positions. (Now part of ASTM E1111.)

ASTM E1376-90(2002), *Standard Test Method for Measuring the Interzone Attenuation of Sound Reflected by Wall Finishes and Furniture Panels*. This laboratory test method measured the degree to which reflected sound is attenuated by the most commonly found vertical surfaces in open-plan spaces. The vertical surfaces covered included wall finishes such as sound-absorbent panels and furniture panels or screens. It did not cover window finishes or furniture other than panels. (Now part of ASTM E1111.)

STRUCTURE-BORNE NOISE

24.22 STRUCTURE-BORNE IMPACT NOISE

The term noise will be used in lieu of sound in the following discussion of structure-borne, impact, and equipment noise control. Although use of the term noise assumes that a decision has been made that a particular sound is unwanted, this is a very reasonable assumption for the situations to be discussed. Use of the term noise gets to the point.

Structure-borne noise is at least as serious a problem as airborne noise for the following reasons:

1. There is no air cushion between the source and the structure; thus, high-intensity energy is introduced into the structure, through which it travels with minimum attenuation and at great speed.

2. Sound, once introduced into the structure, is attenuated well only by discontinuities in the structure. Since the structure must have structural integrity to carry the loads, discontinuities of the type that will stop noise are complex and expensive.

3. The entire structure constitutes a network of parallel paths for sound. Therefore, partial solutions are useless, since sound will find flanking paths. The entire structure must be soundproofed to yield good results.

4. Unlike the case of airborne noise, additional mass does not usually block structure-borne noise, particularly in long spans where a floor can act as a

diaphragm, thereby improving the structure-to-air noise transfer efficiency (like a drum).

5. The increasing use of exposed structural ceilings eliminates the attenuation that can be introduced by a plenum above a hung ceiling. This is particularly bad, since most structure-borne noise is carried by floor structures (rather than walls), which radiate sound up and down. The discussion that follows will be limited to impact noise. Refer to Section 24.26 for a brief treatment of vibration, which is felt rather than heard and is, in effect, a very low-frequency noise. Many of the practices and techniques that will minimize impact noise will also reduce vibration.

24.23 CONTROL OF IMPACT NOISE

Impact noise problems can be controlled in two ways—by preventing or minimizing the impact and by attenuating it once it has occurred. Prevention is discussed first; attenuation is covered in Section 24.24. Impact on floors is more serious than wall impact because the latter is partially attenuated at the wall/floor joint, whereas the former is introduced directly into the building framework. The following discussion addresses each of the solutions shown in Fig. 24.43.

(a) Cushion the Impact

See Fig. 24.43*a*. This obvious solution will frequently eliminate all but severe problems. Resilient cushioning materials in common use are floor tile of rubber and cork, or carpeting on pads, in ascending order of impact insulation. See Section 24.24 and Appendix K for quantitative data on impact isolation.

(b) Float the Floor

See Fig. 24.43*b*. Since the key to elimination of structure-borne sound is *isolation*, separating the impacted floor from the structural floor by a resilient element is extremely effective. This element can be rubber or mineral wool pads, or blankets, or special spring metal sleepers. The effectiveness depends upon the mass of the floating floor, compliance of the resilient support, and degree of isolation of the floating floor. The last element is extremely important, since flanking paths via end contacts with walls can short-circuit the floating element's sound impedance and defeat the system. With floating floors it is important that:

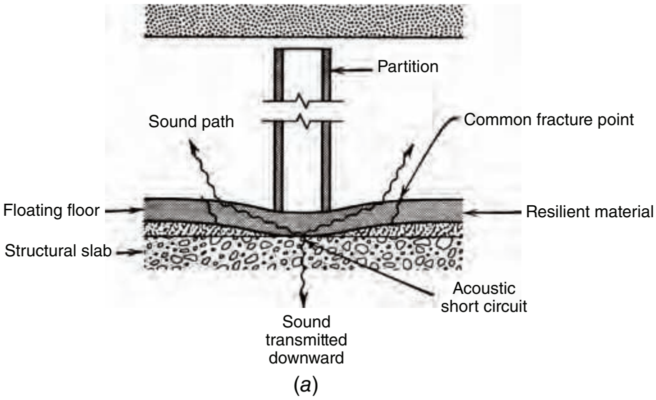
1. The mass of the floating floor be large enough to spread the loads properly. Otherwise, the pad will compress and deform sufficiently to transmit the impact.
2. Total construction be airtight. Airtight is soundtight.
3. Particular care be exercised where partitions rest on the floating floor (see Fig. 24.44*a*).
4. Short circuits at walls or by penetrations be avoided; see Fig. 24.10*b*. Details of proper construction techniques are given in *A Guide to Airborne, Impact and Structure-Borne Noise Control in Multifamily Dwellings* (HUD, 1968).
5. Construction throughout be consistent. Mixed construction types invite flanking noise paths (see Fig. 24.44*b*).

(c) Suspend the Ceiling—and Use an Absorber in the Cavity

See Fig. 24.43*c*, *d*. As stated, the most disturbing noise is that radiated down from the ceiling. A flexibly suspended ceiling with an acoustic

Cushion impact (*a*) Float floor (*b*) Suspend ceiling (*c*) Sound absorber in cavity (*d*) Isolate and seal piping, etc. (*e*)

Fig. 24.43 *Methods of controlling impact sound transmission through floors. (Reprinted from* Quieting: A Practical Guide to Noise Control*, NBS, 1986.)*



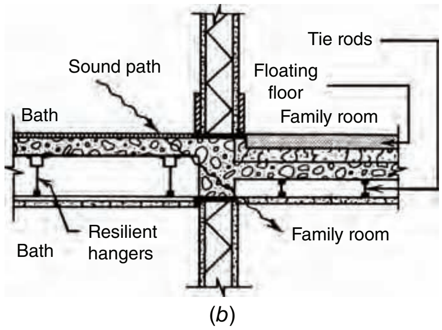


Fig. 24.44 *(a) Caution must be exercised when supporting partitions on floating floors to prevent structural failures or short-circuiting of the floating element, as illustrated. (b) Flanking paths in mixed-construction type floors. The FHA does not recommend mixing construction types unless provisions have been made to prevent flanking (e.g., expansion joints or breaks in all structural paths between spaces). (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*

absorbent layer suspended in it can be very effective if not flanked by paths leading into the walls and from there reradiating into the space below. It is imperative that the entire floor slab above be decoupled from the walls below by resilient separators.

(d) Isolate All Piping

See Fig. 24.43*e*. All rigid structures such as piping must be isolated so as not to form a flanking path, and penetrations must be caulked with resilient sealant so as not to constitute an air–sound leakage path.

24.24 IMPACT INSULATION CLASS

The impact insulation class (IIC) is a single-number, impact isolation rating for floor construction, similar in intent and derivation to STC wall ratings. Tests are made with a standard tapping machine and noise levels measured in ⅓-octave bands. These are plotted and compared to a standard contour, approximately as with the sound transmission class. Details of typical floor constructions along with IIC ratings are given in Appendix K. Resilient floor finishes on any of the floor constructions not specifically provided with them will add to the IIC ratings approximately as follows:

1⁄16-in. (1.6 mm) vinyl tile	0
⅛-in. (3 mm) linoleum or rubber tile	4 ± 1
¼-in. (6 mm) cork tile	10 ± 2
Low-pile carpet on fiber pad	12 ± 2
Low-pile carpet on foam rubber pad	18 ± 3
High-pile carpet on foam rubber pad	24 ± 3

MECHANICAL SYSTEM NOISE CONTROL

24.25 MECHANICAL NOISE SOURCES

Mechanical devices make noise. And generally, the more power they consume, the more noise they make. In many of today's buildings, 40% of the total construction budget is spent on mechanical systems located throughout a building.

In most buildings, the primary sources of mechanical noise are the components of the air-conditioning and air-handling systems such as fans, compressors, cooling towers, condensers, ductwork, dampers, mixing boxes, induction units, and diffusers. The curve of Fig. 24.45 depicts typical air-handling system noise and indicates the portions of the spectrum produced by each group of components. Pumps are another source of mechanical noise, which (along with the noise of flowing liquid) is transmitted along pipes to locations throughout the building.

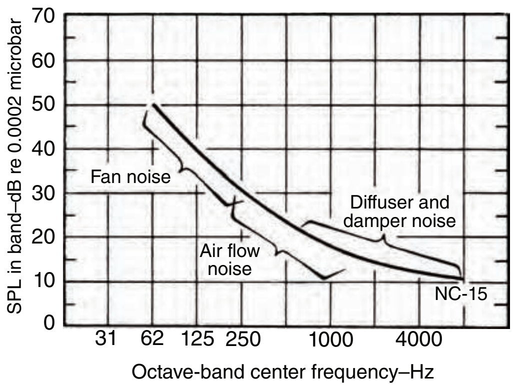


Fig. 24.45 *Sound pressure level frequency spectrum of noise from HVAC system components.*

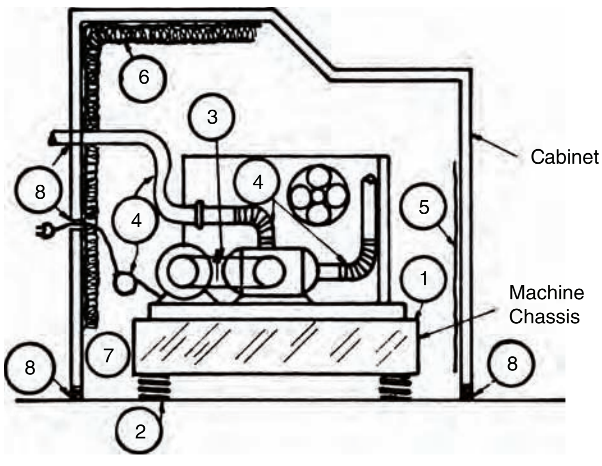
Elevators, escalators, and freight elevators also introduce mechanical noise into buildings. Escalators and freight elevators pose few problems, since they are localized in a specific area and have low operation speeds. Passenger elevator car operation, however, is rapid, and it affects large areas. In addition, the motors and controls are located on or above the prime upper floors of a building. Motor, shaftway, and other equipment noise must be properly controlled to prevent annoyance to building tenants located near the shaftways, elevator penthouses, or mechanical equipment rooms. Vibration isolation of these major components is a specialized problem beyond the scope of this book.

24.26 QUIETING OF MACHINES

Machines cause noise by vibration. This noise is imparted directly to the surrounding air and by vibrational contact to the surrounding structure. Therefore, there are three ways to reduce this noise:

1. Reduce the vibration itself.
2. Reduce the airborne noise by decoupling the vibration from efficient radiating sources.
3. Decouple the vibrating source from the structure.

Refer to Fig. 24.46. Items 1, 3, and 4 reduce vibration; items 4, 5, 6, and 7 reduce and decouple the vibration from the radiating cabinet; and items 2 and 8 decouple the vibrating source from the structure. Once a noise becomes airborne or



1. Install motors, pumps, fans, etc. on most massive part of the machine.
2. Install such components on resilient mounts or vibration isolators.
3. Use belt drive or roller drive systems in place of gear trains.
4. Use flexible hoses and wiring instead of rigid piping and stiff wiring.
5. Apply vibration damping materials to surfaces undergoing most vibration.
6. Install acoustical lining to reduce noise buildup inside machine.
7. Minimize mechanical contact between the cabinet and the machine chassis.
8. Seal openings at the base and other parts of the cabinet to prevent noise leakage.

Fig. 24.46 *Techniques used to reduce the transmission of airborne and structure-borne noise from machines and appliances. (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*

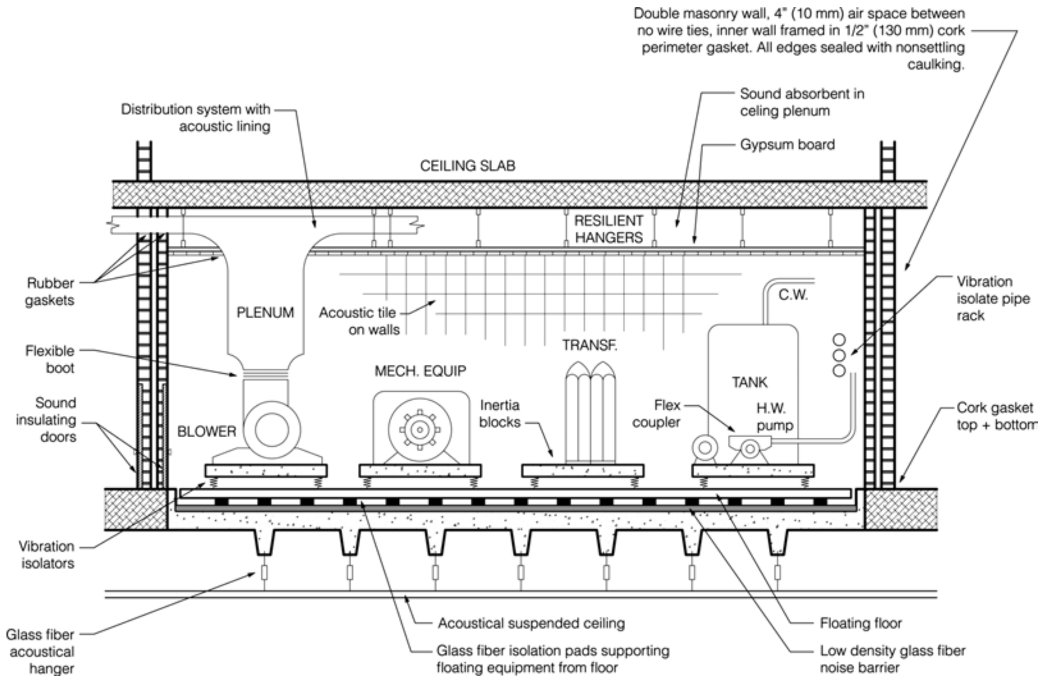


Fig. 24.47 *Soundproofing a mechanical equipment room. Additional noise reduction to the space below can be achieved by inserting a layer of highly absorbent material in the space above the suspended acoustical ceiling. (Redrawn by Wesley Thompson from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings, *HUD, 1968.)*

structure-borne, the aforementioned isolation techniques are employed.

Vibration reduction takes two forms, damping and isolation. One form of damping is accomplished by rigidly coupling the vibrating source to a large mass, frequently called an *inertia block*. Much of the energy is absorbed and dissipated as friction; the remainder results in lower-amplitude vibration (Fig. 24.47). Isolation is accomplished by supporting the vibrating mass on resilient supports. These take many forms and can be used in combinations. Thus, machines are supported on fibrous, rubber, or spring steel vibration isolators, and the entire mass can be supported on a floating floor, which in turn rests on resilient vibration isolators, as in Fig. 24.47. Large machines are supported on special commercial "sandwiches" of asbestos, lead, cork, and other strong, resilient materials. Piping is supported on cork pads and hung on resilient hangers.

Use of a diesel-driven electric generator for load peaking or cogeneration can cause very serious noise and vibration problems. The ideal solution to this situation is to completely isolate the unit in a separate outbuilding that is designed specifically to contain the very high noise level produced. If that is not practical and an inside location is necessary, a complete enclosure may be required to ameliorate the noise problem.

Vibration damping can be an even more serious problem, which can be solved satisfactorily with sufficient mass and proper vibration isolation. In the case of vibrating sheet metal, soft foam-type damping material glued directly to the metal is effective in damping. Flexible joints in all pipes and ducts connected to vibrating machines are mandatory. This includes flexible conduit connectors to all motors, transformers, and lighting fixtures using magnetic ballasts.

24.27 DUCT SYSTEM NOISE REDUCTION

Design of a quiet duct system entails more than specifying an absorptive duct lining. Air turbulence generates noise. Turbulence increases as the velocity of airflow increases and anywhere in the duct system where smooth laminar flow is disturbed, such as at sharp bends. The permissible "sharpness" of a bend depends in turn upon air velocity; the higher the air velocity, the more aerodynamic the duct system must be to prevent turbulence and, therefore, noise. Table 24.10 demonstrates this principle. The farther one proceeds upstream from a point of turbulence, the higher the air velocity may be from a noise perspective, since truly laminar flow is essentially noiseless. In principle, velocities should be as low as practical, since air turbulence noise increases exponentially with velocity.

Sound travels as easily against as with the airflow in ductwork. Therefore, both supply and return systems must be lined to control transmission of fan noise. Maximum fan noise reduction occurs at bends in the ductwork. For maximum fan noise reduction in short runs, a pair of 90° bends is sometimes deliberately inserted. However, because 90° bends also introduce turbulence that generates noise, introducing bends as fan noise attenuators can be counterproductive at air velocities above 600 fpm (3 m/s). Another disadvantage of bends is added system friction and the additional energy and cost required to move air. This point will be discussed further in the next section.

Other design approaches that create a quiet system include smooth transitions at changes of duct size and large-radius bends with turning vanes, the purpose of which is to reduce turbulence. Attenuation drops rapidly as duct size increases; therefore, ducts should not be deliberately oversized. Cross-talk between rooms and between ducts can be minimized by using lined ducts, separating adjacent ducts as much as possible, and gluing damping material on the outside and lining on the inside. Damping material is particularly effective in preventing the thin metal walls of ducts from resonating. Mufflers and silencers are effective in reducing the high-frequency components of fan noise, but much less so with low frequencies. The pressure drop these devices introduce, which can be considerable, must be compensated for in the fan selection.

The *ASHRAE Handbook—HVAC Applications* should be consulted for recommendations on noise control in air-handling units, plenums, housings, and ducts. Figure 24.48 shows some of the ways in which cross-talk and flanking noises can be reduced. Figure 24.49 shows some techniques employed for quieting duct noise. Active noise cancellation (see Section 24.28) is particularly useful in duct systems since it does not reduce airflow, as do liners, baffles, and other mechanical silencing devices, and it is effective at low frequencies, whereas these devices are not.

The increased use of variable air volume (VAV) systems has introduced some noise problems that should not be neglected. VAV system noise can be minimized by following a few basic design rules. Maintain minimum system static pressure, since fan noise increases exponentially with static pressure. Select the air volume modulating device at the fan with care, because it can be a noise source. Since outlet air volume control involves duct area restriction, with attendant velocity increase and resultant noise, such a design must include some sort of downstream silencing equipment. Ceiling diffuser acoustic characteristics must be coordinated with design air velocity and with any requirement for masking sound. Finally, avoid the use of throttling dampers on ceiling diffusers since a partially closed damper can generate very high noise levels.

TABLE 24.10 Maximum Air Speeds in Ducts to Yield NC-15 or NC-25 Background Levels[a]

	Supply		*Return*	
Location	**NC-15**	**NC-25**	**NC-15**	**NC-25**
Slot speed at min. ½-in. (13-mm) opening	250 fpm	350 fpm	300 fpm	420 fpm
10 ft (3 m) of duct before opening	300	420	350	490
Next 20 ft (6 m)	400	560	450	630
Next 20 ft (6 m)	500	700	570	800
Next 20 ft (6 m)	640	900	700	980
Next 20 ft (6 m)	800	1120	900	1260
Next 20 ft (6 m)	1000	1400	1100	1540
Next 20 ft (6 m)	1300	1820	1450	2030
Next 20 ft (6 m)	1600	2240	1800	2520

[a]Ducts with 1- to 2-in. (25- to 50-mm) thick inside duct lining, all duct sizes.

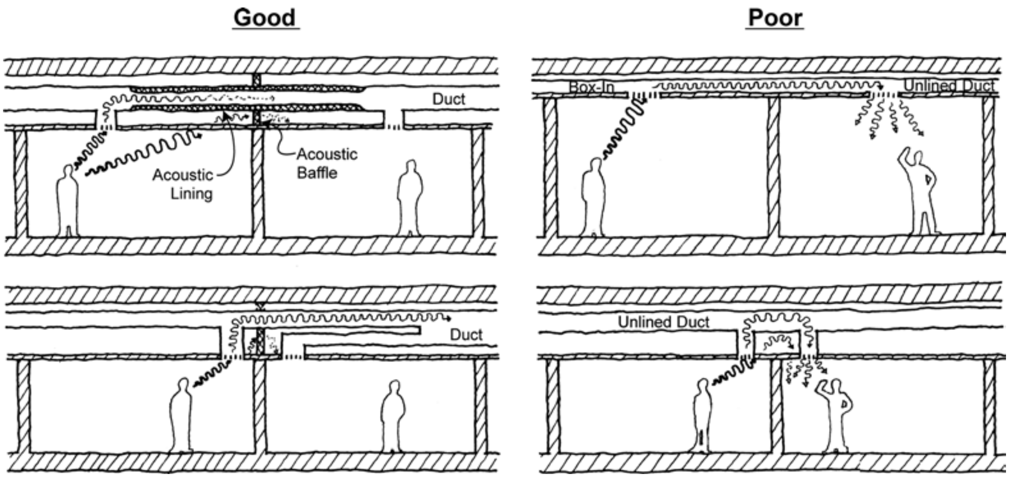


Fig. 24.48 *Since ducts are efficient sound transmission paths, precautions must be taken to avoid cross-talk, ventilation air noise, and equipment noise. Avoid running ducts as a common supply or return between rooms unless they are properly baffled and lined with sound-absorbing material. The common practice, in wood-frame structures, of using troughs between joists as a common return duct between rooms and between separate dwelling units results in serious noise transmission problems. Caulk or seal around ducts at all points of penetration through partitions. Use double-wall ducts, acoustical lining, flexible boots, and resilient hangers where required. Dwelling units should be serviced by separate supply and return ducts that branch off a main duct system. (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD, 1968. Redrawn by Jonathan Meendering.)*

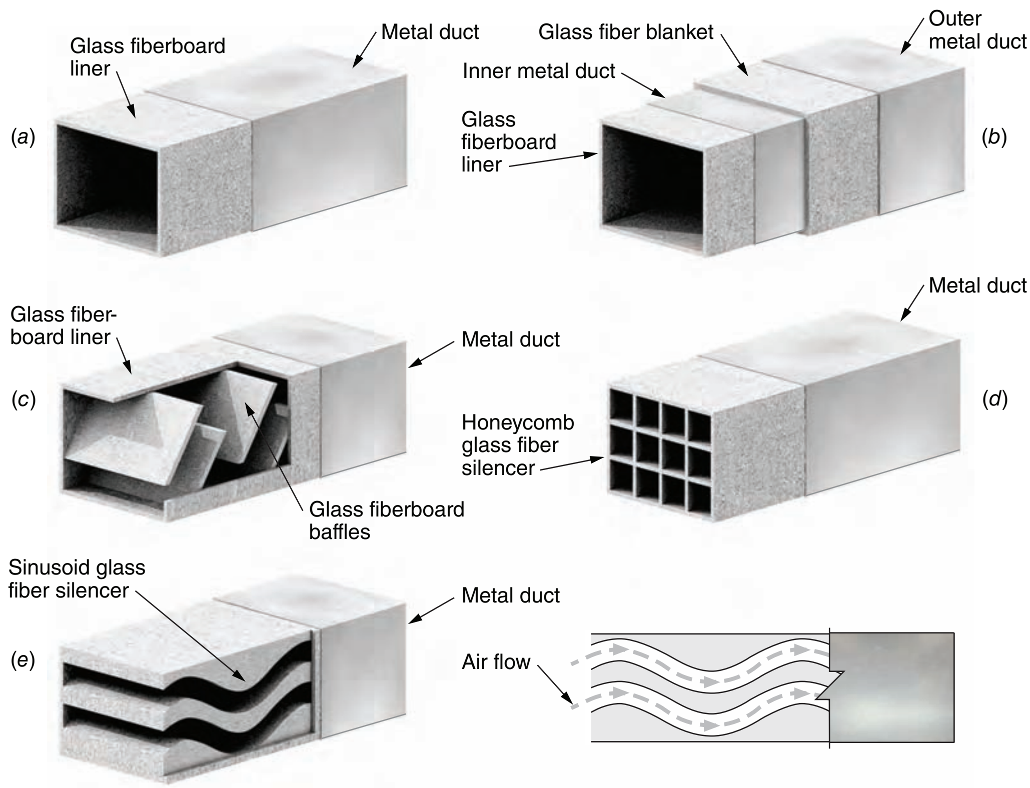


Fig. 24.49 *Unlined duct has negligible sound attenuation. Inside lining (a) gives 2–3 dB attenuation per foot in the range 1–2 kHz, dropping rapidly above and below those frequencies and giving negligible low-frequency attenuation. Double lining (b) gives higher attenuation and reduces cross-talk between ducts. Duct silencers and baffles (c–e) give high broadband attenuation: a maximum of 10–12 dB/ft (3.0–3.7 dB/m) in the range 1–2 kHz and lower above and below. They are useful to reduce fan noise in short runs but cause considerable pressure drop.*

24.28 ACTIVE NOISE CANCELLATION

Since noise is a phenomenon consisting of acoustic wave energy transmitted at certain frequencies, it is theoretically possible to *eliminate* (not mask) noise by simultaneous transmission of identical wave energy exactly out of phase with the noise. The sum of the two energy waves is zero—hence silence (Fig. 24.50). The phase matching, however, must be exact; if the injected out-of-phase noise is not precisely a negative image of the original noise, then not only will the signals not cancel, but they may even increase the noise level. The technique for accomplishing noise cancellation is straightforward in theory but much less so in practice. A microphone samples a noise source and feeds that signal into an analysis/synthesis device. This, as the name implies, analyzes the frequency and amplitude content of the noise and synthesizes the anti-noise, which is then fed to a loudspeaker in the original noise path. The resultant residual noise is detected by a downstream microphone and fed back into the controller as a feedback correction signal. This entire procedure is shown in block diagram form in Fig. 24.51. The technical problems that must be overcome are formidable. Without delving deeply into the physics involved, we can describe them qualitatively.

1. It takes a finite amount of time to analyze the frequency content of a noise and to synthesize the anti-noise. If the noise is random it will have changed by the time the anti-noise signal is injected, and will therefore not be canceled. As a result, *the only type of noise that can effectively be attenuated by anti-noise is one that is continuous and/or predictable.* Random noise, such as that of a barking dog, cannot be actively attenuated with the present technology. Candidates for noise cancellation are sounds like those produced by operating machinery, that is, continuous and repetitive sounds. This includes very-low-frequency noise.

2. The analysis and synthesis process is achieved by a device called an *adaptive digital filter*. For technical reasons, the higher the frequencies (pitch) involved, the more complex and expensive are the required digital electronics, microphones, and loudspeakers. This further narrows the range of practical noise-cancellation candidates to those producing low frequencies, such as blowers, fans, rotors, internal combustion engines and their exhausts, transformers (hum), air movement in ducts, fluid movement in pipes, and the like.

3. The waveform of the noise, its modes, and its dispersion in space impact heavily on the type and amount of equipment required to effect attenuation economically (i.e., commercially). The simplest type of noise to treat is one that is confined by some sort of waveguide, at low frequency, and exhibits constant sound pressure and phase. Such a wave is known as a *plane wave*, and it can be “treated” with a single sampling microphone, a single loudspeaker, and a single processor.

Considering the three stated criteria, an ideal candidate for economic noise-cancellation treatment is duct noise, which is low frequency, continuous, and a plane wave. Figure 24.52 shows the construction of a typical commercial duct-noise-suppression unit, plus application photographs. Practical duct-noise-cancellation equipment in use today can reduce levels from NC-50 to NC-35 and is particularly effective at the “rumble” frequencies below 200 Hz.

Important auxiliary advantages of active duct-noise cancellation are energy conservation and economic benefits. Passive duct-noise reduction, particularly at low frequency, requires large noise absorbers, requiring 7 to 10 ft (2.1 to 3.0 m) of duct for installation. See Fig. 24.49*c–e*. In addition to the high first cost of these devices and their installation, they introduce a static pressure loss of ½ to 1½ in. w.g. (125 to 375 Pa), depending upon airflow and speed. This, in turn, requires a higher horsepower (and noisier) fan. Economic analysis of such designs generally shows an advantage for active noise-cancellation equipment. Such an analysis

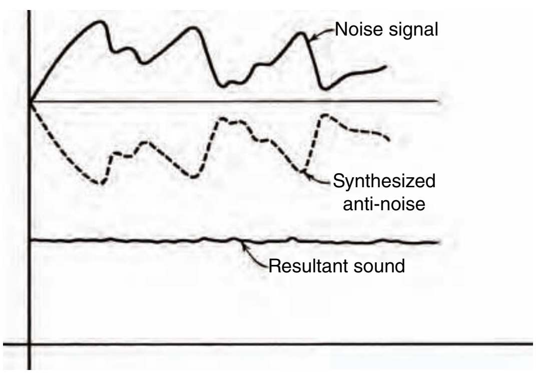


Fig. 24.50 *Silencing of noise by introduction of a synthesized noise signal exactly out of phase with the original signal. The resultant sound is effectively zero—that is, silence.*

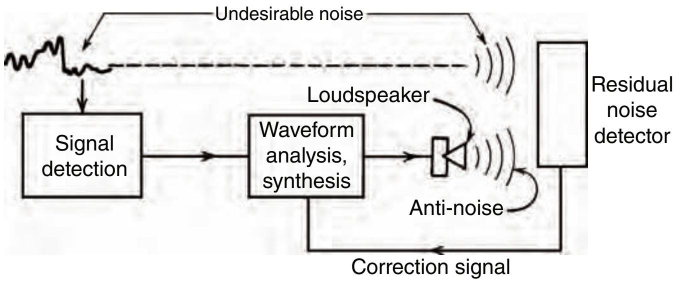


Fig. 24.51 *Block diagram of an active noise-cancellation system. The noise signal is detected, its periodicity determined, its waveform analyzed, and an out-of-phase noise is synthesized and injected into the acoustic environment. A residual noise detector provides a feedback signal that acts to improve noise cancellation.*

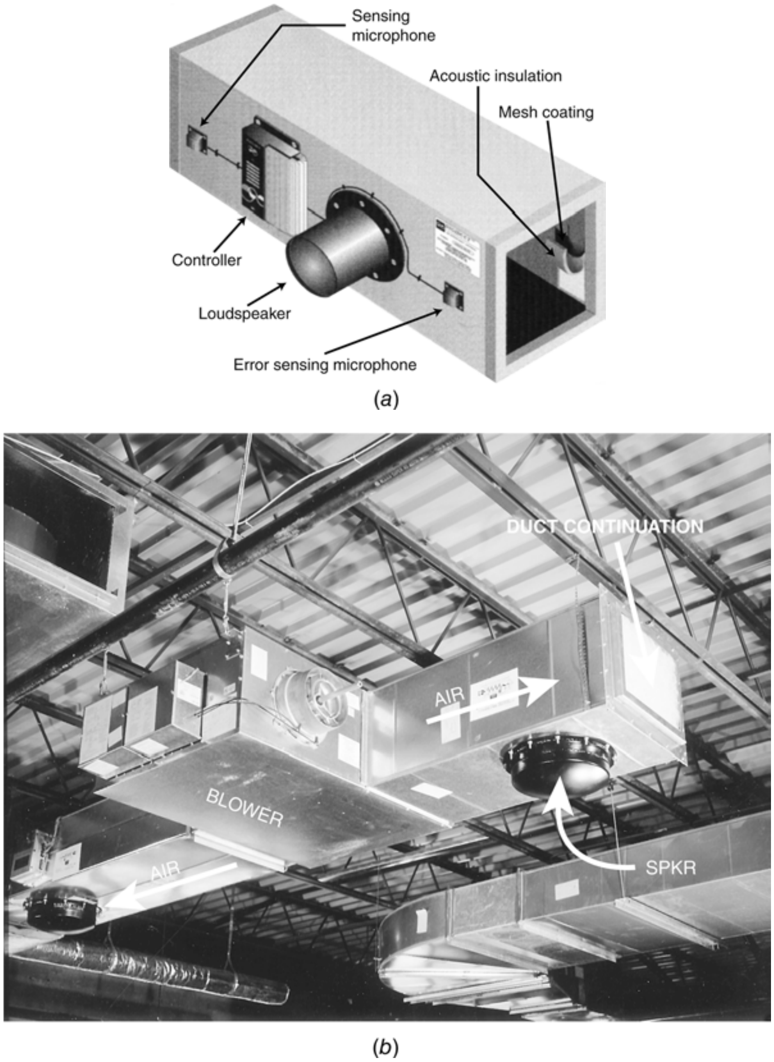


Fig. 24.52 *Active duct-noise-cancellation equipment. (a) The system components—consisting of the sensing and error-signal microphones, controller, and a loudspeaker—are built into a duct section of the required size, which is inserted into the duct system. (b) Photograph of a multichannel duct-noise-cancellation system in a new office building (designed with large, unlined HVAC ducts). (Courtesy of Digisonix.)*

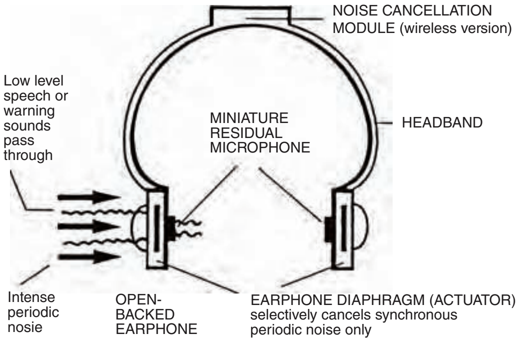


Fig. 24.53 *Schematic diagram of a headset with active noise cancellation. Because of the physical proximity of all the elements, only a single microphone is used. (Courtesy of Noise Cancellation Technologies.)*

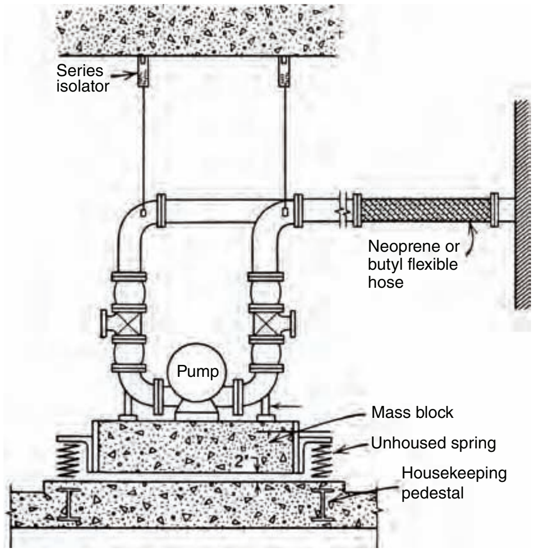


Fig. 24.54 *Typical pump installation with appropriate vibration isolation and damping measures.*

should be performed for every design where duct silencers are desired or required.

Another important application of active noise cancellation, already in wide use, is in the area of hearing conservation for people exposed to high noise levels at work. Here the out-of-phase noise is introduced into miniature loudspeakers (earphones) in an acoustically transparent headset. This allows the wearer to hear random sounds (such as speech) clearly, while repetitive cyclic noise from engines and the like is attenuated (Fig. 24.53).

Other areas where active noise cancellation is already in use include engine exhausts, heavy machine vibration, interiors of luxury automobiles, military and space vehicles, and selected shipboard spaces. Applications will undoubtedly increase with advances in digital signal processing technology, equipment miniaturization, and reduction in equipment costs.

24.29 PIPING SYSTEM NOISE REDUCTION

As with airflow, noise increases exponentially with liquid flow velocity. Piping is not a major noise source normally, since the radiating diameter is small, except for flow velocities much in excess of 8 fps (2.4 m/s) where a pipe is in contact with the structure. This is, of course, most serious where a pipe passes through NC-15 to NC-25 areas (see Table 24.8). Domestic water system mains should be limited to 50 psi (345 kPa) in other than tall buildings, and pressure in branches limited to 35 psi (240 kPa). In high-rise structures, pressure-reducing valves will be required in high-pressure mains to meet these recommendations. Piping must be designed to prevent water hammer, and noise sources must be located away from quiet areas.

Pumps, like all rotating equipment, are sources of vibration and noise and should be treated as described in Section 24.26. Figure 24.54 shows a typical pump installation with appropriate noise reduction measures. For at least a distance of 100 pipe diameters beyond the pump, resilient pipe hangers should be used. With centrifugal pumps, as with fans and blowers, machine sound concentrates in narrow bands and, if extremely disturbing, can be attenuated with resonant filters. Reciprocating pumps are more difficult to control, as the pulsations are more vibration than noise. Flexible connections and U-joints in the piping will absorb much of this vibration.

24.30 ELECTRICAL EQUIPMENT NOISE

Electrical equipment is generally overlooked as a noise source, and this is unwise. Most electrical noise is a 120-Hz hum. This can be very disturbing because the frequency is so low and, as we have noted repeatedly, low-frequency noise is difficult to attenuate passively. Transformer noise levels are dictated by National Electrical Manufacturers Association (NEMA) and American National Standards Institute (ANSI) standards. For a premium price, lower-noise units are obtainable. Table 24.11 lists

TABLE 24.11 Maximum Sound Levels: Dry-Type Transformers

kVA	Decibels (NEMA Standard)
0–9	40
10–50	45
51–150	50
151–300	55
301–500	60

maximum sound levels for dry-type units. Most manufacturers warranty noise below these levels. Oil- and silicone-filled units are normally quieter than dry-type transformers, as are units designed for lower temperature rise. Transformer noise can be minimized by these steps:

1. Mount the unit on vibration isolators.
2. If the transformer is wall-hung, use resilient hangers. If it is floor-mounted, place it on a massive slab if possible.
3. Locate the unit so that reflections do not amplify the sound. Sound-absorbent material on the walls behind the units is not useful at 120 Hz. Only cavity resonators will absorb appreciable amounts of sound at that frequency.
4. Use only flexible conduit connections.
5. Avoid locating transformers adjacent to, or immediately outside, quiet areas. A common error in this regard is placing a transformer pad immediately below the window of an NC 15–25 area.

The second major source of 120-Hz hum is conventional core-and-coil discharge lamp ballasts. These include magnetic ballasts for fluorescent and all high-intensity discharge (HID) sources. Fortunately, electronic ballasts, which are practically noiseless, are rapidly replacing core-and-coil ballasts in fluorescent fixtures, and to a lesser extent in HID units. Table 24.12 lists recommended applications of non-electronic fluorescent ballasts. Conventional coil-type HID ballasts can be very noisy, and care must be exercised in their placement. With all ballasts, the method of mounting has a marked effect on the radiated noise. As pointed out earlier, when a small vibrating source is coupled rigidly to a larger body, noise is amplified because of increased source-to-air coupling. Since core-and-coil fluorescent ballasts for linear fluorescent lamps are necessarily closely coupled to large metal fixtures for heat dissipation purposes, the sound radiation is greatly amplified. A large number of such fluorescent fixtures mounted in a plenum can create a serious noise problem. Solution of the problem lies either in ballast replacement or in the use of absorptive material in plenums, flexible conduit connection to fixtures, and resilient fixture hanging. In severe cases, ballasts can be remote-mounted. Coil-type HID ballasts are inherently noisier than fluorescent ones but, like ballasts for compact fluorescent lamps, are generally less troublesome, being coupled to small radiating bodies.

24.31 NOISE PROBLEMS DUE TO EQUIPMENT LOCATION

Roof-mounted HVAC units have proven to be very economical and very noisy. Vibration, short duct runs, and sound reflections are serious problems that can be solved with vibration isolators, sound mufflers, and careful location of equipment. Roof-mounted cooling towers are a particular problem when they are located adjacent to a taller building. This problem has led to a spate of lawsuits and noise control legislation in many cities. For this reason, particular attention should be paid to all exterior equipment during the design process.

In high-rise buildings, problems are caused by conflicts between the stringent noise requirements of the prime upper floor space and the near presence of elevator machine rooms, mechanical equipment rooms, and cooling towers. These problems are almost impossible to solve after construction and require the services of an acoustics expert during design.

TABLE 24.12 Acoustic Criteria for Selection of Conventional Core-and-Coil Fluorescent Lamp Ballasts

For an Installation in:	Use of Ballasts with This Rating Will Usually Be Satisfactory
TV or radio station, church, synagogue	A
Office, residence, library, reception or reading room, school study hall	B
Noisy office, doctor's or dentist's office, classroom	C
Industrial applications	D

24.32 SOUND ISOLATION ENCLOSURES, BARRIERS, AND DAMPING

In buildings with concentrated high-level noise sources, such as certain types of machinery, it is always more desirable to reduce the noise at its source than to attempt to treat the larger enclosing space. This is most effectively accomplished by enclosing the noise source with materials that provide a combination of reverberant noise reduction by absorption (as explained in Section 23.9 and Fig. 23.10) and blocking of airborne sound with high transmission loss (as detailed in Sections 24.7 to 24.12). These materials are available in the form of curtains, panels, and prefabricated partial and full enclosures tailored to the specific characteristics of the noise source (Fig. 24.55). Such enclosures are not normally the responsibility of the building designer. It is, however, important to know that they will be used, as well as their characteristics, so that appropriate isolation can be designed into the building for the residual sound that is radiated from the enclosures.

Where a noise is at least partially the result of vibrating (sheet) metal enclosures, as for instance on laundry machines, mixers, bins, chutes, polishing drums, and the like, a very effective noise control technique is to damp the vibration. This can be done by permanent attachment of a layer of foam to the vibrating metal, which, by minute flexing of the foam mass, converts the vibration energy to heat. The noise reduction can be further enhanced by adding a heavy, limp barrier material to the outside of the foam. Such combinations are called *composite damping barrier materials*, several of which are illustrated in Fig. 24.56. The foam layer also acts to decouple the barrier and thereby increase the noise attenuation.

Fig. 24.55 *Flexible, lightweight noise absorber. The quilted noise absorber can achieve a noise reduction coefficient of up to 0.88 at a frequency of 500 Hz, dissipating sound energy via transmission from the outermost membrane to the inner fibers. The absorber is ASTM-E84 Class I fire rated, and highly resistant to abrasion. (Courtesy of Industrial Noise Control, Inc.)*

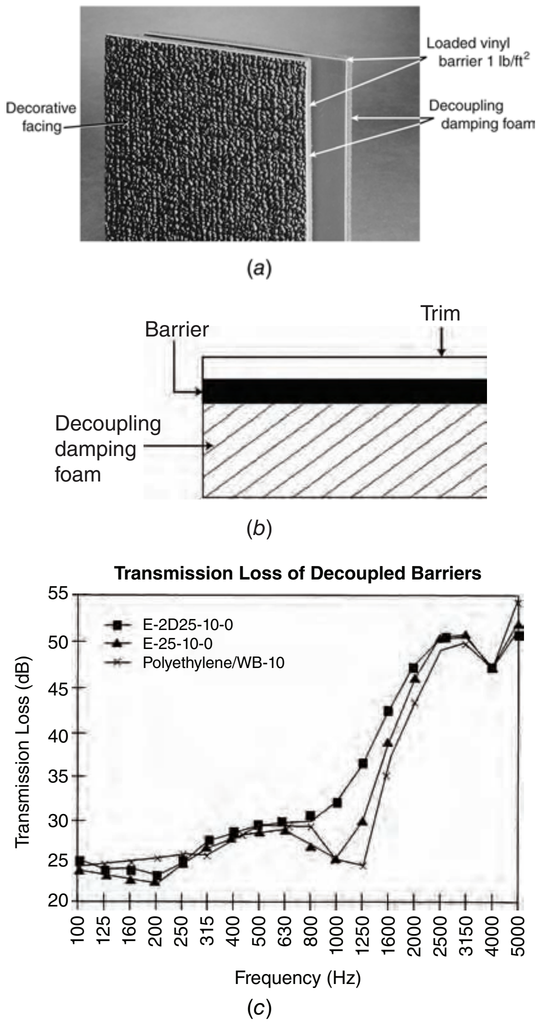


Fig. 24.56 *Composite damped, decoupled barrier material comprising a layer of damping foam plus an integral layer of loaded vinyl barrier material. The exterior may be covered (a) with a decorative cover layer. The foam layer acts to damp the vibrating surface to which it adheres (b) and to decouple the barrier layer. Preliminary attenuation test data (c) for a composite consisting of ¼ in. (6.4 mm) foam and 1 lb/ft² (4.9 kg/m²) loaded vinyl. (Courtesy of E-A-R Specialty Composites, division of Aearo Co.)*

STC AND IIC RECOMMENDATIONS AND CRITERIA

Recommendations for background noise levels (NC criteria) are given in Table 24.8. Criteria for partition isolation (STC) and impact isolation (IIC) are given in the following sections and in Table 24.13.

24.33 MULTIPLE-OCCUPANCY RESIDENTIAL STC/IIC CRITERIA

The most important acoustical design criteria for residential work in the United States are issued by the Department of Housing and Urban Development in conjunction with the Federal Housing Administration (HUD/FHA). The reader is referred to the latest issue of *A Guide to Airborne, Impact and Structure-Borne Noise Control* and to subsequent HUD/FHA publications. Tables 24.14 and 24.15 give the essential data presented in the current edition of the *Guide*.

The recommendations are divided into grades I, II, and III. Grade II is the most important category and is applicable primarily in residential urban and suburban areas considered to have an average noise environment. The nighttime exterior noise levels may be about 40 to 45 dBA, and the permissible interior noise environment characteristics should

TABLE 24.13 Recommended STC for Partitions; Specific Occupancies

	Wall, Partition, or Panel Between		*Sound Isolation Requirement: Background Level in Room Being Considered*	
Type of Occupancy	**Room Being Considered and**	**Adjacent Area**	**Quiet**	**Normal**
Normal school buildings without extraordinary or unusual activities or requirements	Classrooms	Adjacent classrooms	STC 42	STC 40
		Corridor or public areas	STC 40	STC 38
		Kitchen and dining areas	STC 50	STC 47
		Shops	STC 50	STC 47
		Recreation areas	STC 45	STC 42
		Music rooms	STC 55	STC 50
		Mechanical equipment rooms	STC 50	STC 45
		Toilet areas	STC 45	STC 42
	Music practice rooms	Adjacent practice rooms	STC 55	STC 50
		Corridor and public areas	STC 45	STC 42
Executive areas, doctors' suites; confidential privacy requirements	Office	Adjacent offices	STC 50	STC 45
		General office areas	STC 48	STC 45
		Corridor or lobby	STC 45	STC 42
		Washrooms and toilet areas	STC 50	STC 47
Normal office; normal privacy requirements; any occupancy using rooms for group meetings	Office	Adjacent offices	STC 40	STC 38
		Corridor, lobby, exterior	STC 40	STC 38
		Washrooms, kitchen, dining	STC 42	STC 40
	Conference rooms	Other conference rooms	STC 45	STC 42
		Adjacent offices	STC 45	STC 42
		Corridor or lobby	STC 42	STC 40
		Exterior of building	STC 40	STC 38
		Kitchen and dining areas	STC 45	STC 42
Large offices, drafting areas, banking floors, etc.	Large general office areas	Corridors, lobby, exterior	STC 38	STC 35
		Data-processing area	STC 40	STC 38
		Kitchen and dining areas	STC 40	STC 38
Motels and urban hotels, Hospitals and dormitories	Bedrooms	Adjacent bedrooms[a]	STC 52	STC 50
		Bathroom[a]	STC 50	STC 45
		Living rooms[a]	STC 45	STC 42
		Dining areas	STC 45	STC 42
		Corridor, lobby, or public spaces	STC 45	STC 42

Source: Courtesy of U.S. Gypsum.

[a]Separate occupancy.

TABLE 24.14 Criteria for Airborne Sound Insulation of Partitions between Dwelling Units

Partition Function between Dwellings			
Apt. A		**Apt. B**	**Grade II STC**
Bedroom	to	Bedroom	52
Living room	to	Bedroom[a]	54
Kitchen[b]	to	Bedroom[a]	55
Bathroom	to	Bedroom[a]	56
Corridor	to	Bedroom[a,c]	52
Living room	to	Living room	52
Kitchen[b]	to	Living room[a]	52
Bathroom	to	Living room	54
Corridor	to	Living room[a,c,d]	52
Kitchen	to	Kitchen[e]	50
Bathroom	to	Kitchen	52
Corridor	to	Kitchen[a,c,d]	52
Bathroom	to	Bathroom	50
Corridor	to	Bathroom[a,c]	48

Source: Reprinted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings* (HUD, 1968). For Grade I, add 3 points; for Grade III, subtract 4 points.

[a]Whenever a partition wall may serve to separate several functional spaces, the highest criterion must prevail.

[b]Or dining or family or recreation room.

[c]It is assumed that there is no entrance door leading from the corridor to the living unit.

[d]Criterion applies to the partition. Doors in corridor partitions must have the rating of the partition, not vice versa.

[e]Double wall construction is recommended to minimize kitchen impact noises.

TABLE 24.15 Criteria for Airborne and Impact Sound Insulation of Floor-Ceiling Assemblies between Dwelling Units

Assembly Function between Dwellings			*Grade II*	
Apt. A		**Apt. B**	**STC**	**IIC**
Bedroom	Above	Bedroom	52	52
Living room	Above	Bedroom[a]	54	57
Kitchen[b]	Above	Bedroom[a,c]	55	62
Family room	Above	Bedroom[a,d]	56	62
Corridor	Above	Bedroom[a]	52	62
Bedroom	Above	Living room[e]	54	52
Living room	Above	Living room	52	52
Kitchen	Above	Living room[a,c]	52	57
Family room	Above	Living room[a,d]	54	60
Corridor	Above	Living room[a]	52	57
Bedroom	Above	Kitchen[c,e]	55	50
Living room	Above	Kitchen[c,e]	52	52
Kitchen	Above	Kitchen[c]	50	52
Bathroom	Above	Kitchen[a,c]	52	52
Family room	Above	Kitchen[a,c,d]	52	58
Corridor	Above	Kitchen[a,c]	48	52
Bedroom	Above	Family room[e]	56	48
Living room	Above	Family room[e]	54	50
Kitchen	Above	Family room[e]	52	52
Bathroom	Above	Bathroom[c]	50	50
Corridor	Above	Corridor	48	48

Source: Reprinted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings* (HUD, 1968). For Grade I, add 3 points; for Grade III, subtract 4 points.

[a]This arrangement requires greater impact sound insulation than the converse, where a sensitive area is above a less sensitive area.

[b]Or dining or family or recreation room.

[c]It is assumed that plumbing fixtures, appliances, and piping are installed with proper vibration isolation.

[d]The airborne STC criteria in this table apply as well to vertical partitions between these two spaces.

[e]This arrangement requires equivalent airborne sound insulation and perhaps less impact sound insulation than the converse.

not exceed NC 25–30. Grade I is suburban, with a quiet noise environment characterized by a nighttime exterior noise level of about 35 to 40 dBA. *Grade I STC/IIC criteria are 3 points higher than those of grade II.*

The fundamental criteria for airborne sound insulation between dwelling units are, for grade II:

Wall partitions	STC > 52
Floor-ceiling assemblies	IIC > 52

These apply where similar function spaces are contiguous, such as bedroom to bedroom and living room to living room. Where this is not the case, the isolation must be increased to meet the higher sensitivity requirement.

Grade III recommendations are minimal and can be characterized as noisy, with an average nighttime exterior noise level of about 55 dBA or higher. *Grade III STC/IIC recommendations are 4 points lower than those of grade II.*

24.34 SPECIFIC OCCUPANCIES

(a) Schools

School buildings house spaces of many kinds—classrooms, auditoriums, gymnasiums, cafeterias, shop areas, swimming pools, and music suites—that pose acoustical problems.

1. *Auditoriums.* All auditoriums require a sound system for some of the activities accommodated (see Figs. 23.24 to 23.27). The most difficult aspect, architecturally, is integration of a loudspeaker system into the design. To provide proper sound reinforcement, loudspeakers must be located properly without large obstructions. To accomplish this, the loudspeaker system should be incorporated in the earliest design stages.

In general, a school auditorium is a multipurpose facility. It should be designed to meet speech requirements and also should be suitable for the school's music activities. Often a modified gymnasium (gymnatorium) or cafeteria (cafetorium) functions as an auditorium. Acoustic compromises will need to occur in such facilities. Large areas of sound-absorbing treatment in either kind of space make them unsuitable as auditoriums and for most events that require speech amplification.

2. *Classrooms.* Typical classrooms are approximately 30 ft square (2.8 m^2) with 10-ft (3-m) ceilings. Adequate speech communication is easily achieved in a room of this size. Classroom acoustic design usually involves:

a. Locating sound-absorbing treatment to reduce classroom noise levels
b. Ensuring adequate privacy between adjacent spaces
c. Control of air-handling system noise

Acoustic tile ceilings provide adequate sound absorption for most classrooms. An NRC of 0.7 is recommended (see Section 23.10).

Partition systems must produce sufficient isolation to prevent disturbance from activities in other classrooms and corridors. Such partitions should run full-height from floor to ceiling slab or roof construction. If return air transfer ducts are needed, their noise reduction characteristics must be as good as those of the walls or doors that they penetrate (for NC data, see Table 24.8). Unit ventilators commonly used for classrooms produce approximately the required level of background sound.

3. *Music suites.* School music programs usually range from individual instruction to band and choral concerts. The teaching spaces required for such a program include practice rooms, ensemble rooms, and large rehearsal spaces. Both room acoustics design and sound isolation are important in music suites. Privacy between adjacent spaces is critical, since simultaneous use is necessary.

4. *Dining areas.* The activity in cafeterias or lunchrooms usually generates a great deal of noise. The kitchen and serving areas should be separated from the eating spaces. Ceilings and wall areas in the cafeteria should be treated with sound-absorbing material. Unless the ceiling is completely treated with a highly effective sound-absorbing material, the environment will be unsatisfactory due to its high noise level. The minimum NRC of this material should be 0.8.

5. *Gymnasiums.* Activities in gymnasiums create so much noise that even extensive treatment will not quiet these spaces. A quiet gymnasium probably would be unsatisfactory in any case, since spectators are conditioned to consider the noise as an enjoyable aspect of athletic events. However, to provide a proper environment for normal sports activities, the ceiling area should absorb sound. In addition, if a sound amplification system is to be used, sound-absorbing wall treatment may be required to eliminate echoes that would reduce the intelligibility of announcements. An NRC of 0.7 is suggested with sound-absorbent material to be ceiling-mounted.

If a gymnasium will also serve as an auditorium, loudspeaker system placement requires special consideration. For example, the loudspeakers should be located above the source location for speeches and plays.

6. *Swimming pools.* The acoustic environment of swimming pools is often chaotic. Most sound-absorbing materials disintegrate in the high-humidity conditions prevalent in pool areas. Use special sound-absorbing units that have moisture-resistant properties.

7. *Shops.* Metal, woodworking, and scenery shops in schools contain many noise sources—saws, planers, drill presses, and manual tools. Each generates high airborne and structure-borne noise levels. Consolidating noisy areas and maximizing the distance between them and quiet spaces are essential. Ceiling and wall absorptive treatment with an NRC of at least 0.75 is recommended.

(b) Houses of Worship

The basic activities of these buildings usually combine speech and music. Thus, the worship environment must be acoustically hospitable to both. The architectural plan also must respond to religious requirements, including the relative positioning of pulpits, lecterns, the altar (if any), and the choir.

Successful acoustics can be achieved by designing the overall environment for music and providing special assistance for speech. Large congregational spaces frequently include a sound-reflecting canopy over the pulpit to direct the speaker's voice to the congregation. In some large buildings, a loudspeaker located above the canopy further reinforces speech from the pulpit. The choir and organ communicate with the entire volume of the building and, therefore, benefit from a reverberant environment.

(c) Offices

Although office buildings may contain public spaces, auditoriums, and restaurants, prime occupancy is in office areas. Most acoustics problems in office buildings relate to privacy—either between spaces within a single firm or between adjacent firms. Speech privacy is discussed at length in Sections 24.16 through 24.21, including consideration of open-plan offices. Mechanical and electrical equipment noise problems are discussed in Sections 24.25 through 24.32.

(d) Apartment Buildings

Large apartment buildings house hundreds and even thousands of residents. Privacy and freedom from annoyance are high on the list of tenant requirements. See the HUD/FHA criteria in Section 24.33.

The performance of partitions is compromised in many designs by careless planning of convenience outlets, medicine cabinets, and mechanical services. Direct-exhaust duct connections between apartments and back-to-back placement of medicine cabinets result in loss of privacy. Back-to-back convenience outlets must be avoided.

Installation of rugs or carpeting provides the best protection against footfall noise. Many leases now require that a tenant provide such impact-reducing floor covering over most of the floor area in an apartment. Good design also dictates that similar spaces in adjacent apartments ought to be grouped—bedrooms next to bedrooms, for example. Absorptive material in bedrooms should be ceiling mounted. A minimum NRC of 0.6 is recommended.

Apartment house site selection seldom includes consideration of acoustics. Nevertheless, truck routes, superhighways, and airports can be annoying "neighbors." Cooling towers serving adjacent buildings must be considered during the planning stages.

OUTDOOR ACOUSTIC CONSIDERATIONS

24.35 SOUND POWER AND PRESSURE LEVELS IN FREE SPACE (OUTDOORS)

The equations in Section 23.8 are not applicable to outdoor sound propagation, in which the large reflective component of the indoor condition is absent. Although the propagation of sound outdoors may not appear to be of immediate importance in architectural acoustics, outdoor noise sources such as traffic, cooling towers, and aircraft are frequently loud enough to disturb activities within or immediately adjacent to a building. Conversely, the noise made by building equipment such as cooling towers, air-cooled condensers, and even window air conditioners may be loud enough to disturb neighbors in a nearby building. For this reason, it is desirable to have some basic understanding of outdoor sound propagation.

For preliminary evaluation of an outdoor noise problem, assuming a small nondirectional source on the ground, the sound pressure level can be determined from Equations 23.5 and 23.6. For large sources such as cooling towers and traffic, which do not exhibit inverse square properties, sound level estimates are best made on the basis of experience and empirical data beyond the scope of this book (see Magrab, 1975; Schaudinischky, 1976). For small outdoor sources, the equipment power level can be estimated by measuring the sound pressure level at 5 ft (1.5 m) and adding 15 dB. Other factors (such as moisture in the air, the presence of trees, wind, and temperature gradients) will affect outdoor sound propagation to some extent, but they can be ignored except when great distances (i.e., over 1000 ft [305 m]) are involved. Barriers, which are the most effective outdoor attenuators, were discussed in Section 24.14.

24.36 BUILDING SITING

Building siting, vis-à-vis exterior noise sources, is as important as interior structural design. Since this subject is somewhat beyond our scope of concern, the discussion is brief. Buildings should be sited, with respect to noise sources:

1. To use natural terrain noise barriers (Fig. 24.57*a*).
2. Regarding trees as noise barriers, to rely only on very thickly wooded areas (Fig. 24.57*b*).
3. To avoid naturally poor sites (Fig. 24.57*c*).
4. To avoid sound reflection from other buildings (Fig. 24.57*d*)

Point 4 is also important in a multiwing building. Avoid U-shapes or other configurations where a central court can become an echo chamber.

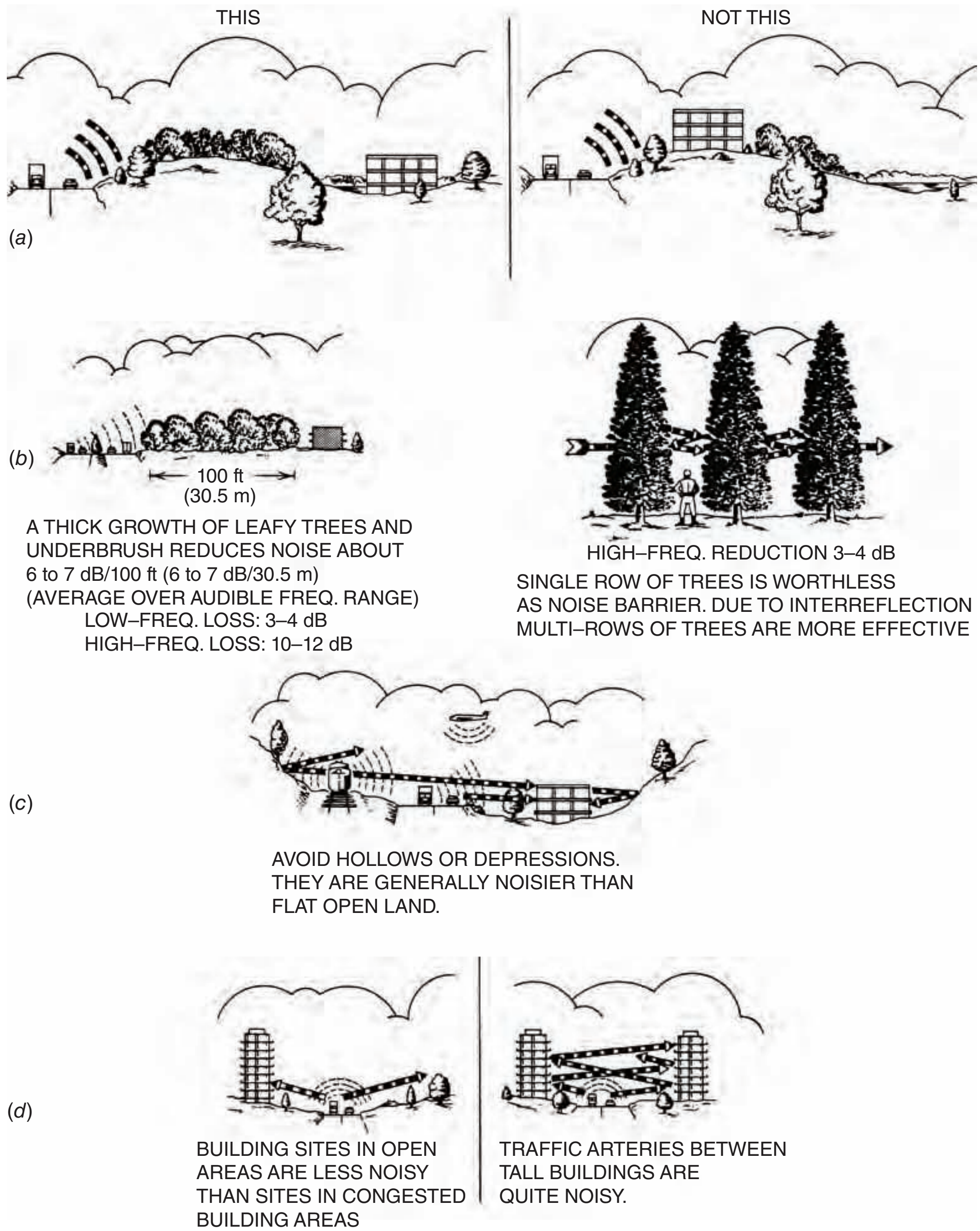


Fig. 24.57 *(a) Use of natural noise barriers. (b) Effectiveness of wooded areas as noise barriers, showing noise reduction of trees. (c) An example of a poor building site. (d) Building site issues near traffic arteries and other buildings. (Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD, 1968.)*

Where avoidance of an exterior noise source is impossible, quiet zones can be buffered from noises by placing higher-noise areas on the noisy side of a building. Thus, in a school, classrooms and offices can be buffered by a cafeteria and gym; in a residence, bedrooms by living rooms and corridors; in an office building, private offices by noisier clerical offices; and so on.

REFERENCE MATERIAL

24.37 GLOSSARY

A-scale. A filtering system with characteristics that roughly match the response characteristics of the human ear. Referred to as dBA.

Absorption coefficient α**.** The ratio of the sound absorbed to the sound incident on a material or device.

Anechoic room. A room that provides a free field acoustic testing environment like the outdoors. All the sound emanating from a source is essentially absorbed at the surfaces of the room.

ANSI. American National Standards Institute, a nonprofit national technical association that publishes standards covering definitions, test methods, recommended practices, and specifications of materials.

Articulation class (AC). A figure of merit for acoustic absorption indicating the absorption efficiency of a material for angles of incidence of the sound wave between 45° and 55°. The range is 150–250 (no units), with higher numbers indicating better absorption.

Articulation index (AI). A numerical index in the range of 0.0–1.0 indicating the degree of speech intelligibility in an open-office design, measured with background noise, including masking sound, if any. Also a measure of speech privacy. An index of 0.0 indicates no speech intelligibility, hence ideal speech privacy; an index of 1.0 indicates perfect speech intelligibility and therefore no speech privacy.

ASTM. Formerly the American Society for Testing and Materials, now simply ASTM, a nonprofit national technical society that publishes definitions, standards, test methods, recommended installation practices, and specifications for materials. ASTM is a consensus group of the building materials industry. It sets standards for products and establishes methods for testing.

Baffle or barrier, sound. A shielding structure or partition used to increase the effective length of a sound transmission path between two locations.

Ceiling attenuation class (CAC). A single number or range of numbers for evaluating the effectiveness of an acoustical ceiling construction in isolating audible airborne sound transmission, tested at 16 one-third-octave frequencies. Higher numbers indicate more effectiveness in preventing noise between rooms. Tested in accordance with ASTM E1414. Previously described as the Ceiling Sound Transmission Class (CSTC) or Sound Transmission Class (STC).

Critical frequency. The lowest frequency at which the wavelength of a bending wave, traveling in a structure, is the same as the wavelength in air at that frequency.

Damping. Dissipation of structure-borne noise. This is usually accomplished by using a material with a high internal energy-absorbing capacity (i.e., high internal damping).

Decibel (dB). A descriptive notation adopted for convenience in representing vastly different sound quantities.

Diffraction. The tendency of sound waves to flow readily around obstacles that are small in comparison to the wavelength of the sound.

Diffuse sound field. A region where sound at any given point is made up of sound waves with all angles of incidence.

Direct sound field. A region in which all or most of the sound arrives directly from the source without reflection.

FIIC. Field impact insulation class, which is determined by an actual field test. Also see *FSTC*, field sound transmission class, also determined by an actual field test.

Flanking sound path. The transmission of sound or noise from one room to another by indirect paths rather than directly through an intervening partition.

Flutter. A multiple echo set up between parallel reflecting surfaces.

Free sound field (free field). A region in a homogeneous medium free from boundaries. In a free field, the sound pressure level decreases 6 dB for a doubling of the distance from a point source.

FSTC. Field sound transmission class, which is determined by an actual field test performed per ASTM E336. Also see *FIIC*, Field impact insulation class, also determined by an actual field test.

Impact insulation class (IIC). A single-figure rating that provides an estimate of the impact-sound-isolating performance of a floor-ceiling assembly.

Intensity. The amount of sound energy per second that is carried across a unit area.

Intensity level (IL). A measure of the acoustic power passing through a unit area expressed in the decibel scale and referenced to some standard base (usually 10^{-12} W/cm^2).

Interference. The destructive or reinforcing action of two or more waves arriving at the same position simultaneously.

Loudness. A subjective human definition of the intensity of a sound.

Masking. The presence of a background sound increases the level to which a sound signal must be raised in order to be heard or distinguished. If the level of the background sound is significantly higher than that of the sound signal, the signal cannot be heard. This effect is known as masking.

Mass law. States that the transmission loss of walls (in part of the frequency range) is controlled entirely by the mass per unit area of the panel. It also states that the transmission loss increases 6 dB for each doubling of frequency or each doubling of the panel mass per unit area.

Noise. Any undesired sounds, usually of different frequencies, resulting in an objectionable or irritating sensation.

Noise reduction (NR). (1) The reduction in sound pressure level caused by making an alteration to a sound source. (2) The difference in sound pressure level measured between two adjacent rooms caused by the transmission loss of an intervening barrier.

Noise reduction coefficient (NRC). The average sound absorption coefficient (to the nearest .05) measured at the four ⅓-octave bands centered on frequencies of 250, 500, 1000, and 2000 Hz.

Octave band. A range of frequency where the highest frequency of the band is double the lowest frequency. The band is usually specified by its center frequency.

Phon. Loudness level, at a particular frequency, equal to the 1000-Hz decibel level of that equal-loudness contour.

Pink noise. Wide-spectrum noise whose amplitude drops 3 dB per octave with increasing frequency (equal energy per octave). Useful for masking.

Random noise. A noise whose magnitude and/or frequency cannot be predicted precisely at any given time. A rough approximation of random noise is the static heard on a radio between stations (see *Noise*, *Pink Noise*, *White Noise*).

Reverberation. A persistence or echoing of previously generated sound caused by reflection of acoustic waves from the surfaces of enclosed spaces.

Reverberation time. The time required for a sound to decay to a value one-millionth of its original intensity or to reduce 60 dB after the sound source has stopped.

Sabin. The unit of acoustic absorption. One sabin (ft^2) (m^2) is the absorption of 1 ft^2 (m^2) of perfect sound-absorbing material or open space with no reflecting surfaces.

Sound absorption coefficient. The fraction of the incident energy absorbed (not reflected) by a material when a sound wave strikes it is the sound absorption coefficient of that material. Usually represented by the Greek letter alpha (α).

Sound barrier. A material installed to prevent the passage of sound from one area to another. Sound-deadening board and lead sheet or special insulation make good sound barriers.

Sound level meter. An instrument for the direct measurement of sound pressure level. Sound level meters may also incorporate octave band filters for measuring sound directly in octave bands.

Sound power level (PWL). A measure of the total airborne acoustic power generated by a noise source, expressed in the decibel scale and referenced to some standard base (usually 10^{-12} W).

Sound pressure level (SPL). A measure of the air pressure change caused by a sound wave.

Expressed in the decibel scale and referenced to some standard base (usually 0.0002 μbar).

Sound transmission class (STC). A single-number rating of a building element's efficacy in blocking the transmission of sound compared to a standard transmission attenuation/frequency curve. See also *Ceiling Attenuation Class*.

Transmission loss (TL). The reduction of airborne sound power caused by placing a wall or barrier between the reverberant sound field of a source and its receiver. Transmission loss is a property of the wall or barrier.

White noise. Noise of a wide frequency range in which the amplitude of the noise is essentially the same in all frequency bands (equal energy per frequency band).

24.38 REFERENCE STANDARDS

See Section 24.21(i) for a description of the contents of these standards.

ASTM C423-09a, *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*

ASTM E90-09, *Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements*

ASTM E336-11, *Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings*

ASTM E413-10, *Classification for Rating Sound Insulation*

ASTM E795-05(2012), *Standard Practices for Mounting Test Specimens During Sound Absorption Tests*

ASTM E1110-06(2011), *Standard Classification for Determination of Articulation Class*

ASTM E1111-07, *Standard Test Method for Measuring the Interzone Attenuation of Open Office Components*

ASTM E1130-08, *Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index*

ASTM E1179-13, *Standard Specification for Sound Sources Used for Testing Open Office Components and Systems*

ASTM E1264-08e1, *Standard Classification for Acoustical Ceiling Products*

ASTM E1374-06(2011), *Standard Guide for Open Office Acoustics and Applicable ASTM Standards*

ASTM E1375-90(2002), *Standard Test Method for Measuring the Interzone Attenuation of Furniture Panels Used as Acoustical Barriers*

ASTM E1376-90(2002), *Standard Test Method for Measuring the Interzone Attenuation of Sound Reflected by Wall Finishes and Furniture Panels*

ASTM E1414 / E1414M-11a, *Standard Test Method for Airborne Sound Attenuation Between Rooms Sharing a Common Ceiling Plenum*

ASTM E1573-09, *Standard Test Method for Evaluating Masking Sound in Open Offices Using A-Weighted and One-third Octave Band Sound Pressure Levels*

ISO (International Organization for Standardization) 717-1, 2013. *Acoustics—Rating of Sound Insulation in Buildings and of Building Elements—Part 1: Airborne Sound Insulation*

ISO 717-2, 2013. *Acoustics—Rating of Sound Insulation in Buildings and of Building Elements—Part 2: Impact Sound Insulation*

24.39 UNITS AND CONVERSIONS

The I-P and SI system of units are used throughout this book. Acoustical measurements will occasionally be expressed in two historic systems of units (that are now generally obsolete). See Table 24.16 for MKS units (employing the meter, kilogram, and second as basic elements) and CGS units (employing the centimeter, gram, and second) and common conversions.

TABLE 24.16 Acoustic Units and Conversions

Variable	MKS units		CGS units
Force	kilogram-meter/s^2 = newton		gram-cm/s^2 = dyne
Intensity	watts/meter^2		watts/cm^2
Pressure	newton meter^2 = pascals		dynes/cm^2 = microbars
	In Conversion:		
Quantity	**Multiply**	**By**	**To Obtain**
Force	newtons	10^5	dynes
	dynes	10^{-5}	newtons
Intensity	watts/cm^2	10^4	watts/m^2
	watts/m^2	10^{-4}	watts/cm^2
Pressure	pascals	10	microbars
	microbar	10^{-1}	pascals

Note: One atmosphere = 1 bar = 10^6 μbar.

24.40 SYMBOLS

See Table 24.17 for abbreviations and symbols that are typically encountered in architectural acoustics.

TABLE 24.17 Symbols and Abbreviations Used Commonly in Acoustics

A	Total absorption, sabins; area in unit being used
A_R	Absorption in receiving room, sabins
$A_{1,2\ldots}$	Total absorption of each material in a space, sabins
AC	Articulation class
c	Velocity of sound, feet per second
CAC	Ceiling attenuation class
d	Distance from source, meters or feet
dB	Decibel
f	Frequency of sound, hertz (Hz)
I	Intensity, W/cm^2
I_a	Absorbed energy, W/cm^2
I_i	Incident energy, W/cm^2
I_0	Reference intensity, 10^{-16} W/cm^2
IIC	Impact insulation class, no units
IL	Intensity level, decibels
NC	Noise criterion, no units
NRC	Noise reduction coefficient, no units
NR	Noise reduction, decibels
p	Pressure, pascals or microbars
p_0	Reference base pressure, 2×10^{-5} Pa
P	Acoustic power, watts
Pa	Pascal, unit of pressure (SI)
PWL	Sound power level, decibels
R	Room constant, square feet (square meters)
r	Distance from source, meters or feet
S	Surface area, in unit being used
SPL	Sound pressure level, decibels
STC	Sound transmission class, no units
T_R	Reverberation time, seconds
TL	Transmission loss, decibels
V	Volume (geometric)
W, P	Sound power, watts
W_0	Reference base sound power, 10^{-12} W
a, α	Absorption coefficient (no units)
$\bar{a}$, $\bar{\alpha}$	Average absorption coefficient (no units)
λ	Wavelength, feet or meters
Σ	Sum of, or total (no units)
$\Sigma S\alpha = \Sigma A$	Total absorption, sabins
Δ	Change in a quantity or difference between two quantities

Note: Where definitions are expressed in I-P units, SI units are also understood, with proper conversion factors, and vice versa.

References and Resources

ASHRAE. 2011. *ASHRAE Handbook—HVAC Applications*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, GA.

Cavanaugh, W. J., W. R. Farrell, P. W. Hirtle, and B. G. Watters. 1962. "Speech Privacy in Buildings." *Journal of the Acoustical Society of America*, Vol. 34, No. 4.

Fader, B. 1981. *Industrial Noise Control.* John Wiley & Sons. Hoboken, NJ.

HUD. 1968. *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*. U.S. Department of Housing and Urban Development. Washington, DC.

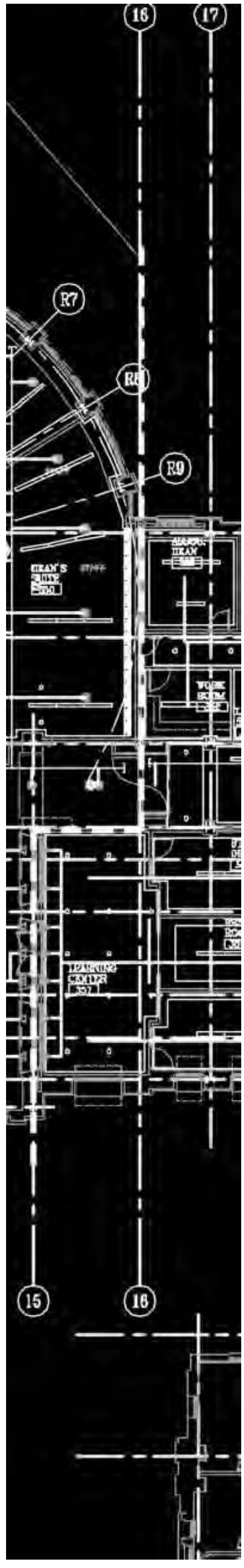
Magrab, E. B. 1975. *Environmental Noise Control.* John Wiley & Sons. Hoboken, NJ.

Schaudinischky, L. H. 1976. *Sound, Man and Building.* Applied Science Publishers. London.

Young, R. W. 1965. "Revision of the Speech Privacy Calculation." *Journal of the Acoustical Society of America*, Vol. 38, No. 4.

PART VI

FIRE PROTECTION



One of the most challenging aspects of building design is providing protection against the effects of fire.

Designers may enjoy making a building comfortably cool on a stifling hot day or well-lit and warm on a bitterly cold night. It is less pleasant to imagine a building burning and considering how its occupants, and then the building itself (along with its contents), can be saved.

To complicate this critically important concern, there are inherent conflicts between some optimum features of fire resistance and some common and useful features of design strategies such as daylighting, passive cooling, or HVAC systems. There are even potential design conflicts between systems for the safe evacuation of people and systems for the suppression of fire—because both people and fire thrive on oxygen. However, there is also some common ground among daylighting, passive and active climate control, acoustics, and fire protection. The challenge is to find the optimum balance.

Design for fire protection is an intriguing challenge. Many aspects of fire protection are rigidly governed by building codes that have evolved over the past 100 years in response to disasters and milestone events. On the other hand, most large buildings include some feature (such as an atrium) that is unique and not clearly addressed by otherwise explicit fire codes. Another challenge is to find an acceptable balance between respect for the codes and ingenuity to move beyond the codes when required.

CHAPTER 25

Fire Protection

JUST AS BUILDINGS CAN BE DESIGNED TO minimize heating, cooling, and lighting equipment and thus to reduce energy consumption, they can be designed to reduce the size of firefighting systems and retard the spread of smoke and fire. As the average size of fires within buildings continues to decline, the emphasis is shifting to minimizing water and smoke damage. Whole-building conflagrations, while spectacular, are relatively rare in large buildings in North America, now that both automatic fire detection and fire-extinguishing systems are widespread.

This discussion of fire protection begins with basic design considerations for fire resistance. Smoke management (for safe evacuation and for limited smoke damage) is considered next, followed by fire-suppression systems such as sprinklers and non-water-based approaches. Lightning protection is then discussed, along with the many fire detection and alarm systems that are keyed to the major stages of the typical building fire.

Throughout this chapter, the influence of the National Fire Protection Association (NFPA) is apparent. The periodically updated *Fire Protection Handbook* is an especially useful source of information for design, from which several illustrations have been reprinted in this text.

FIRE RESISTANCE, EGRESS, AND EXTINGUISHMENT

25.1 DESIGN FOR FIRE RESISTANCE

Fire is a special kind of oxidation known as *combustion*. Oxidation—discussed in previous chapters in terms of rust within water supply equipment and aerobic digestion in waste disposal systems—is a process in which molecules of a fuel are combined with molecules of oxygen, producing a mixture of gases and energy. When this occurs rapidly, as in a fire, energy is released as heat and light, and some gases become visible as smoke. Table 25.1 lists the stages of a fire and the factors that influence its growth. Many of these factors involve decisions made by building designers.

Fire has a triangle of needs: fuel, high temperature, and oxygen. If deprived of any of these needs, building fires will be extinguished. In general, this triangle's influence on building design is as follows. The *fuel* is the building's structure and contents; the designer controls the choice of structural and finish materials, but rarely the final contents. The *temperatures* achieved in fires are well beyond the

TABLE 25.1 Major Factors Influencing Fire Growth

Realm	Approximate Ranges of Fire Sizes	Major Factors That Influence Growth
1 Preburning	Overheat to ignition	Amount and duration of heat flux Surface area receiving heat Material ignitability
2 Initial burning	Ignition to radiation point (10-in. [254-mm] high flame)	Fuel continuity Material ignitability Thickness Surface roughness Thermal inertia of the fuel
3 Vigorous burning	Radiation point to enclosure point (10-in. to 5-ft high flame [254 mm to 1.5 m])	Interior finish Fuel continuity Feedback Material ignitability Thermal inertia of the fuel Proximity of flames to walls
4 Interactive burning	Enclosure point to ceiling point (5-ft [1.5-m] high flame to flame touching ceiling)	Interior finish Fuel arrangement Feedback Height of fuels Proximity of flames to walls Ceiling height Room insulation Size and location of openings HVAC operation
5 Remote burning	Ceiling point to full room involvement	Fuel arrangement Ceiling height Length/width ratio Room insulation Size and location of openings HVAC operation

Source: Reprinted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, National Fire Protection Association®, Quincy, MA 02169.

ability of building cooling systems to control, so special water systems (in the form of sprinklers) are often installed to deprive fire of the high temperatures it needs. *Oxygen* may be denied to a fire partly by limitations on ventilation, but reduced oxygen can have serious safety consequences. Another design response is to install fire-suppression systems that either cover the fuel (foam, dry chemicals) or displace oxygen with another gas—for example, carbon dioxide or "clean agents" that inhibit the chemical action of the flame itself.

(a) Sources of Ignition

Buildings commonly contain three basic sources of ignition: chemical, electrical, and mechanical. In *chemical* combustion, most commonly known as *spontaneous combustion*, some chemicals reach ignition at ordinary temperatures within buildings. Chemical combustion depends upon the rate of heat generation (related to the degree of saturation of combustible products, determined by the chemicals involved), the air supply (enough to supply oxygen but not enough to lower the temperature), and the insulation provided by the immediate surroundings (the more insulation, the easier the attainment of combustion temperatures).

Electrical heat energy is most commonly supplied by resistance heating, a familiar process in many appliances and in space-heating equipment. Less common are electric ignition by induction, dialectic process, arcing, and static electricity. Lightning is an infrequent but enormously destructive electrical energy source.

Mechanical heat energy is produced by friction (including sparks), by overheating of machinery, and occasionally by the heat of compression.

(b) Products of Combustion

Everyone has experienced to some degree the dangers of the *thermal* products of combustion (Fig. 25.1)—flame and heat. These visible and tactile elements of fire can cause burns, shock, dehydration,

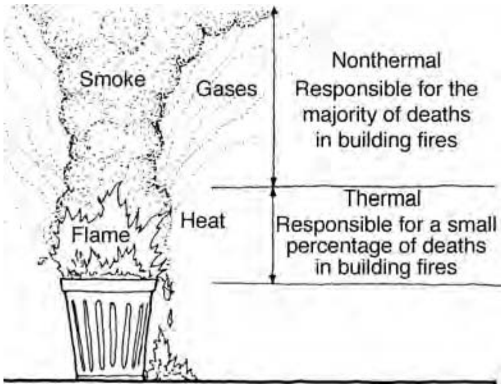


Fig. 25.1 *Although the thermal products from a fire—flame and heat—make strong visible and tactile impressions, fire's nonthermal products—smoke and its constituent components—pose the greater threat to life.*

heat exhaustion, and fluid blockage of the respiratory tract, but they are responsible for only about one-quarter of the deaths resulting from building fires. Most fire deaths are caused by the *nonthermal* products—smoke and its wide range of constituent gases, liquids, and solids. Smoke can usually be seen and smelled. Made up of droplets of flammable tars and small particles of carbon suspended in gases, it irritates the eyes and nasal passages, sometimes blinding and/or choking a person. Gases are especially dangerous because, without visible smoke, they are so often difficult to detect. Some gases are directly toxic, but all are dangerous because they displace oxygen. Common gases released in building fires include carbon monoxide and carbon dioxide.

Carbon monoxide is a deadly product of combustion and is often the most abundant such product. It is produced when insufficient oxygen is available to completely oxidize the burning material. It is more readily attached to hemoglobin molecules in red blood cells than is oxygen, thus depriving the brain and muscles of needed oxygen. This leads to irrational behavior and loss of consciousness, then to death. *Carbon dioxide* is also likely to result from combustion but, unless intentionally introduced into a space as a means of fire suppression, should not be present in concentrations with serious health impacts (beyond potential headaches and dizziness).

Other dangerous and commonly encountered building-fire gases include hydrogen sulfide, sulfur dioxide, ammonia, oxides of nitrogen, cyanide, phosgene, and hydrogen chloride (from burning polyvinyl chlorides found in computers, electronic equipment, and cable jackets). These types of gases may cause eye, skin, nose, and throat irritation—and in sufficient concentrations can be psychotropic and/or toxic.

In indoor fires, oxygen commonly becomes insufficient because the fire consumes it so rapidly. The normal concentration of oxygen in air is about 21%. At less than 17%, muscular coordination and judgment are diminished; at 14% down to 10%, people remain conscious but become irrational, and fatigue is rapid; at 10% down to 6%, collapse occurs, but revival is possible when increased oxygen is supplied. The technique of starving the fire of oxygen can therefore pose a threat to human beings, both by increasing the chances of carbon monoxide production and by depriving people of oxygen.

(c) Objectives in Fire Safety

Many older buildings were designed at a time when building fires usually resulted in the loss of several adjacent structures; hence, the primary objective of firefighting was to limit the conflagration to as few city blocks as possible. With the increased use of fire-resistant construction and code control of site and building planning, fires typically were confined to one building at a time. As fire-suppression systems came into common usage within buildings, it then came to be expected that fires could be confined to one or two floors within a building. Now that automatic detection/suppression systems are technically advanced, fires can usually be confined to one room or to even smaller areas. In the United States, most fires in sprinklered buildings are now extinguished with one to five sprinklers operating.

Four common design intents related to building fire safety, in order of usual importance, are:

1. Protection of life
2. Protection of building
3. Protection of contents
4. Continuity of operation

Many of the elements of building fire safety are covered by building codes, but it is important to remember that codes specify the *minimum* acceptable protection. Designers can go much further than the codes require in order to enhance fire safety. It is also important to realize that codes *cannot* cover all aspects of fire safety, as there are too many variables in building design.

Codes typically *prescribe* design strategies that are *passive* means of limiting the spread of fire and protecting life: wall, floor, and ceiling constructions; maximum open floor areas; maximum distances to exits; and so on. Codes commonly allow some relaxing of such prescriptions when *active* fire-suppression systems (such as sprinklers) are designed into a building. Alternatively, a detailed *computer analysis* of fire spread and occupant evacuation within a proposed project may allow for even greater distances to exits, larger open floor areas, and alternative constructions. This is a *performance-based*, rather than a prescriptive, approach to design. It requires close cooperation between designers and fire code enforcement authorities.

(d) Fire Safety and Other Environmental Control Systems

In some instances, the desirable design approaches for fire safety will track design approaches for lighting, thermal, acoustic, and water systems. Although these opportunities may be uncommon, it would be unfortunate (because of a discipline-centric design process) to miss such synergies as:

Thermal mass is useful for passive heating and cooling systems, for acoustic isolation of airborne sound, and for fire barriers (most thermally massive materials will not burn easily).

High ceilings are useful for daylight distribution and displacement ventilation, but also for collecting a large quantity of smoke before it reaches the occupants and for allowing smoke and/or flames from a fire to be seen from a greater indoor distance.

Windows, useful for daylight, ventilation, and view, also allow access for firefighting and rescue, provide escape routes, relieve smoke accumulation with fresh air, and thus relieve some of the stress of trapped occupants.

Solid (*noncombustible*) *overhangs over windows* not only provide sunshading, but also discourage the vertical spread of fire over the building face and can serve as emergency exterior places of refuge.

Elevated water storage tanks provide both adequate water pressure for plumbing fixtures and water for firefighting in the first few minutes of a fire before firefighters arrive.

In many other instances, there are potential design conflicts between building performance under ordinary conditions and building performance in the extraordinary event of a fire. Escalators invite shoppers to explore the upper levels of a department store or connect hotel lobbies to ballrooms; they are also efficient apertures for the vertical spread of fire and smoke. (Special fire protection strategies for escalators are found in Chapter 34.) Daylighting and natural ventilation are best served by high ceilings and low partitions, which encourage light and air from the perimeter to pervade building interiors. If unchecked by sprinklers, however, fire and smoke can easily spread through such open floor plans. (On the other hand, smoke and fire can build up much more rapidly in small, enclosed rooms that retain heat.) Forced-air systems that heat, ventilate, and cool are also potential pathways for smoke and fire; this hazard is especially serious when the systems penetrate floors, because vertically spreading fires are harder to fight than horizontally spreading ones. (Then again, carefully designed forced-air systems can aid in smoke management.) Windowless buildings that rely on electric lighting in place of daylight are especially dangerous in fires because firefighters cannot easily evacuate occupants or gain access to the building. Sunscreens that completely cover windows are disadvantageous for the same reason; nonoperable windows, although considered advantageous for tightly controlled air conditioning, must be broken for fire evacuation/access. The higher the window, the greater the danger from falling shards of glass. Many excellent insulating materials will burn readily, and some will give off toxic gases. Some of the loveliest interior finishes are both flammable and deadly sources of gases in a fire. Table 25.2 summarizes fire requirements for interior finishes.

The dichotomy between ensuring comfort throughout a building's normal life and safety at the moment it is threatened by fire is the principal reason that codes alone cannot ensure fire safety. The dilemma of ordinary versus extraordinary performance must be faced by the cooperative actions of the designer, owner, and occupants of a building.

(e) Protection of Life

The NFPA *Fire Protection Handbook* discusses human behavior in fires in great detail. Although

TABLE 25.2 Summary of Life Safety Code Requirements for Interior Finish

Occupancy	Exits	Access to Exits	Other Spaces
Assembly—New: >300 people	A I or II	A or B I or II	A or B
≤300 people	A I or II	A or B I or II	A, B, or C
Assembly—Existing: >300 people	A	A or B	A or B
≤300 people	A	A or B	A, B, or C
Educational—New	A I or II	A or B I or II	A or B; C on low partitions[a]
Educational—Existing	A	A or B	A, B, or C
Day Care Centers—New	A I or II	A I or II	A or B NR
Day Care Centers—Existing	A or B	A or B	A or B
Group Day-Care Homes—New	A or B I or II	A or B	A, B, or C
Group Day-Care Homes—Existing	A or B	A, B, or C	A, B, or C
Family Day-Care Homes	A or B	A, B, or C	A, B, or C
Health Care—New AS* Mandatory	A NA	A B on lower portion of corridor wall[a]	A B in small individual rooms[a]
Health Care—Existing	A or B	A or B[a]	A or B[a]
Detention and Correctional—New	A or B I or II	A or B I or II	A, B, or C
Detention and Correctional—Existing	A or B I or II	A or B I or II	A, B, or C
Residential, Board and Care[b]			
Residential, Hotels and Dormitories—New	A I or II	A or B I or II	A, B, or C
Residential, Hotels and Dormitories—Existing	A or B I or II	A or B I or II	A, B, or C
Residential, Apartment Buildings—New	A I or II	A or B I or II	A, B, or C
Residential, Apartment Buildings—Existing	A or B I or II[a]	A or B I or II[a]	A, B, or C
Residential, 1- and 2-Family, Lodging or Rooming Houses	A, B, or C	A, B, or C	A, B, or C
Mercantile—New	A or B I or II	A or B	A or B
Mercantile—Existing Class A or B	A or B	A or B	Ceiling A or B; Walls A, B, or C
Mercantile—Existing Class C	A, B, or C	A, B, or C	A, B, or C
Office—New	A or B I or II	A or B I or II	A, B, or C
Office—Existing	A or B	A or B	A, B, or C
Industrial	A or B I or II	A, B, or C I or II	A, B, or C
Storage	A or B I or II	A, B, or C	A, B, or C

Source: Reprinted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, National Fire Protection Association®, Quincy, MA 02169.

[a]See occupancy chapters of NFPA 101 for details.

Notes: Class A Interior Wall and Ceiling Finish—flame spread 0–25, (new) smoke developed 0–450.

Class B Interior Wall and Ceiling Finish—flame spread 26–75, (new) smoke developed 0–450.

Class C Interior Wall and Ceiling Finish—flame spread 76–200, (new) smoke developed 0–450.

Class I Interior Floor Finish—critical radiant flux, minimum 0.45 Watts/cm^2.

Class II Interior Floor Finish—critical radiant flux, minimum 0.22 Watts/cm^2.

*Automatic sprinklers (AS)—where a complete standard system of automatic sprinklers is installed, interior finish with flame spread rating not over Class C may be used in any location where Class B is normally specified, and with rating of Class B in any location where Class A is normally specified; similarly, Class II interior finish may be used in any location where Class I is normally specified, and no critical flux rating is required where Class II is normally specified. (This does not apply to new health care facilities.)

Exposed portions of structural members complying with the requirements of heavy timber construction may be permitted.

panic behavior drives many code requirements, such behavior has been found to be rare. Designers should consider how building occupants make decisions in a fire. In the first phase, cues are detected—the smell of smoke, sounds associated with a fire (breaking glass, sirens, alarm bells), and, more rarely, the sight of flames. Open plans (with longer visible indoor distances) are more amenable to exposing such clues to a wider population. In the second phase, the occupants define the situation: Just how serious is this fire? The more numerous the cues, the more rapid the definition phase. How other people are reacting is influential, and in the absence of strong cues can actually lead to a group refusal to evacuate in the early stages of a fire. In the third phase, coping behavior begins: fight or flight? Clear exit pathways and access to firefighting equipment are critical to rationally making this decision.

For most low-rise buildings, a reasonable goal is the evacuation of all occupants in the time interval between the detection of a fire and the arrival of the firefighters. Designers can provide clearly defined pathways to exits (*exit access*) that can be kept relatively clear of smoke (Fig. 25.2). To accommodate a wheelchair, a minimum clear width of 32 in. (813 mm) is required. *Exits* can take a variety of forms. Vertical exits (Figs. 25.3 and 25.4) include smokeproof towers, exterior and interior stairs and ramps, and escalators that meet specific requirements. *Vertical exits do not include elevators*; they are too easily stalled or, worse, opened at the floor of a fire by malfunctioning signal equipment. Exits in the horizontal plane include doors leading directly to the outside, 2-hour fire-rated enclosed hallways, and moving walks. Special *horizontal exits* are provided by internal firewalls penetrated by two fire doors—one swinging open in either direction. *Exit discharge* is the area outside an exit that leads to a public way and may still need protection in a fire.

Maximum allowable distances to exits are specified in Table 25.3. These are influenced by past experience with people exiting through smoke, especially when it may involve briefly traveling toward the perceived fire location (as in the case

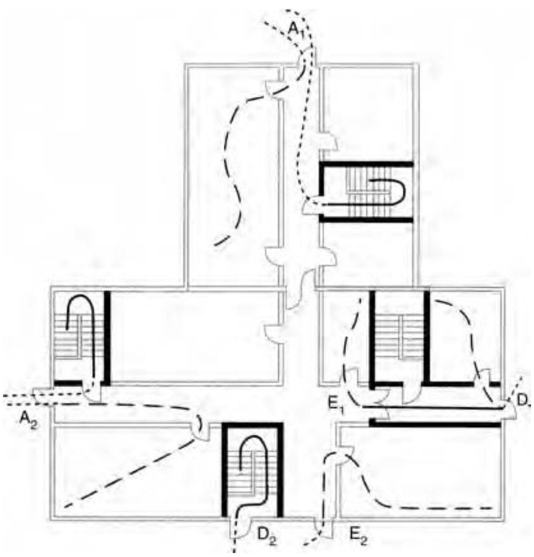


Fig. 25.2 *Exit access, exit, and exit discharge on the first floor of a multistory building. Doors A_1, A_2, E_1, and E_2 are exits, and the path (dashed line) is the exit access. To the person emerging from the exit enclosure, doors A_1 and A_2 and the paths (dotted lines) are the exit discharge. Doors D_1 and D_2 are exit discharge doors. Solid-line paths are within the exit. (Reprinted with permission from the* Fire Protection Handbook, *20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269.)*

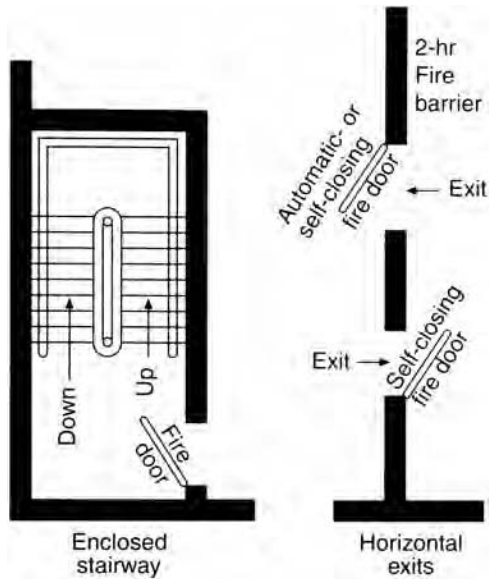


Fig. 25.3 *Plan views of exits. Stair enclosure prevents a fire on any floor from trapping the persons above. A smokeproof tower is better, as it opens to the air at each floor, largely preventing the chance of smoke in the stairway. A horizontal exit provides a quick refuge and lessens the need for a hasty flight down the stairs. Fire-rated doors must be arranged to be self-closing or automatic-closing by smoke detection. (Reprinted with permission from the* Fire Protection Handbook, *20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269.)*

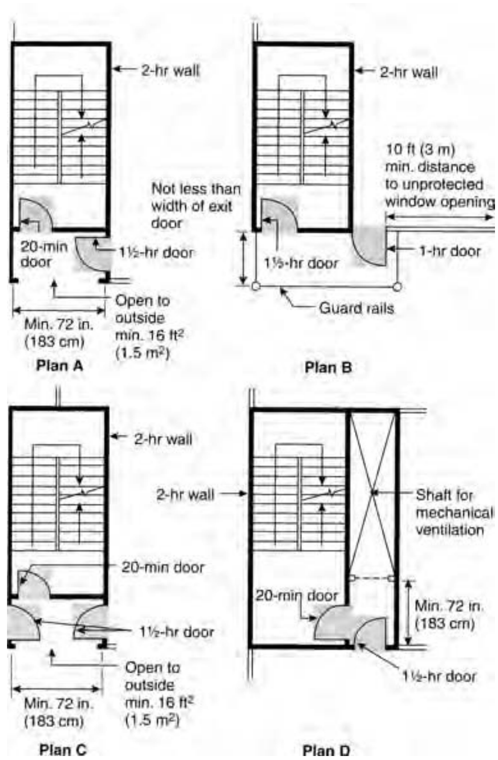


Fig. 25.4 *Four variations of smokeproof towers. Plan A has an open-air vestibule opening from a corridor. Plan B shows an entrance by way of an outside balcony. Plan C could provide a stair tower entrance common to two areas. In plan D, smoke and gases entering the vestibule would be exhausted by a natural or induced draft in the open air shaft. In each case, a double entrance to the stair tower with at least one side open or vented is characteristic of this type of construction. Pressurization of the stair tower in the event of fire provides an attractive alternative for tall buildings and is a means of eliminating the entrance vestibule. (Reprinted with permission from the* Fire Protection Handbook*, 20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269.)*

of a dead-end corridor). When automatic fire suppression systems such as sprinklers are used, the allowable distances to exits are increased. Designers should remember, however, that at least 30% of building fire deaths result from fire cutting off the paths to exits.

Minimum egress widths per floor are found with the help of Table 25.4. First, calculate the floor area (net or gross, as specified in the table). Divide the floor area by the occupant load to determine the number of occupants for whom exits must be provided for that floor. Then calculate the exit capacity based on its clear width. Stairs are sized to meet the requirements of Table 25.5.

EXAMPLE 25.1 A multistory office building is 80 ft (24 m) wide by 300 ft (80 m) long. What exit capacity is required per floor?

SOLUTION (I-P units)

The gross floor area = 80 × 300 = 2400 ft^2. From Table 25.4, "business" categories are based on one person per gross 100 ft^2.

The population per floor is, therefore, (2400 ft^2)/(100 ft^2/person) = 240 people.

Exit doors (to stairs): 240 people × 0.2 in./person = 48 in. total.

(One 34-in. clear door into each of two stairs = 2 doors × 34 = 68 in., more than the minimum.)

Stairs: 240 people × 0.3 in./person = 72 in. total.

(Two stairs at 44 in. each = 88 in., more than the minimum.) ■

The building population as estimated for fire safety is usually much greater than the population for which HVAC, water, or elevator service is designed. The stairs must be designed to allow those already within the stairwell to continue down without interference from access doors on any floor. Stairs with direct access to outdoor air at each floor—so-called smokeproof towers—are the safest kind. A fire stair must allow firefighters to move up while occupants are moving down. Another phenomenon is *reentry*, in which occupants who have exited decide to reenter despite the danger. (Rescue of family members, pets, and valuables is a common reason.) This greatly complicates downward flow.

High-rise buildings present much more difficult problems because firefighting equipment can ordinarily reach no higher than seven floors (about 90 ft [27 m]) and because, typically, only two exit stairways are provided. This difficulty is recognized in building codes, which classify buildings with an occupiable floor more than 75 feet above the lowest fire department access as *high-rise* with special design considerations. Downward flow rates in stairs were formerly assumed at about 45 persons/minute/22 in. (559 mm) of width, but more recently, peak flows of only 24 persons/minute/22 in. (559 mm) have been observed. With a typical exit stair, a 15-story building housing 60 persons per floor per stair can be evacuated in about 9 minutes. However, with the same stair in a 50-story building housing 240 persons per floor per stair, evacuation will take at least 2 hours, 11 minutes! When doors

TABLE 25.3 Common Path, Dead End, and Travel Distance Limits

Type of Occupancy	Common Path Limit — Unsprinklered ft (m)	Common Path Limit — Sprinklered ft (m)	Dead-End Limit — Unsprinklered ft (m)	Dead-End Limit — Sprinklered ft (m)	Travel Distance Limit — Unsprinklered ft (m)	Travel Distance Limit — Sprinklered ft (m)
ASSEMBLY						
New	20/75[a] (6.1/23)	20/75[a] (6.1/23)	20[b] (6.1)	20[b] (6.1)	200[c] (61)	250[c] (76)
Existing	20/75[a] (6.1/23)	20/75[a] (6.1/23)	20[b] (6.1)	20[b] (6.1)	200[c] (61)	250[c] (76)
EDUCATIONAL						
New	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)	200 (61)
Existing	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)	200 (61)
New Day-Care Center	75 (23)	100 (30)	20 (6.1)	50 (15)	150[d] (45)	200[d] (61)
Existing Day-Care Center	75 (23)	100 (30)	20 (6.1)	50 (15)	150[d] (45)	200[d] (61)
HEALTH CARE						
New	NR	NR	30 (9.1)	30 (9.1)	NA	200[d] (61)
Existing	NR	NR	NR	NR	150[d] (45)	200[d] (61)
New Ambulatory Care	75[e] (23)	100[e] (30)	20 (6.1)	50 (15)	150[d] (45)	200[d] (61)
Existing Ambulatory Care	75[e] (23)	100[e] (30)	50 (15)	50 (15)	150[d] (45)	200[d] (61)
DETENTION AND CORRECTIONAL						
New-Use Conditions II, III, IV	50 (15)	100 (30)	50 (15)	50 (15)	150[d] (45)	200[d] (61)
V	50 (15)	100 (30)	20 (6.1)	20 (6.1)	150[d] (45)	200[d] (61)
Existing-Use Conditions II, III, IV, V	50[f] (15)	100[f] (30)	NR	NR	150[d] (45)	200[d] (61)
RESIDENTIAL						
Hotels and Dormitories						
New	35[g,h] (10.7)	50[g,h] (15)	35 (10.7)	50 (15)	175[d,i] (53)	325[d,i] (99)
Existing	35[g] (10.7)	50[g] (15)	50 (15)	50 (15)	175[d,h] (53)	325[d,i] (99)
Apartments						
New	35[g] (10.7)	50[g] (15)	35 (10.7)	50 (15)	175[d,i] (53)	325[d,i] (99)
Existing	35[g] (10.7)	50[g] (15)	50 (15)	50 (15)	175[d,h] (53)	325[d,h] (99)
BOARD AND CARE						
Small, New and Existing	NR	NR	NR	NR	NR	NR
Large, New	NA	125[h] (38)	NA	15 (15)	NA	325[d,i] (99)
Large, Existing	110 (33)	160 (9)	50 (15)	50 (15)	175[d,i] (53)	325[d,i] (99)
Lodging and Rooming Houses	NR	NR	NR	NR	NR	NR
One- and Two-Family Dwellings	NR	NR	NR	NR	NR	NR
MERCANTILE						
Class A, B, C						
New	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)	250 (76)
Existing	75 (23)	100 (30)	50 (15)	50 (15)	150 (45)	250 (76)
Open-Air Covered Mall	NR	NR	0 (0)	0 (0)	NR	NR
New	75 (23)	100 (30)	20 (6.1)	50 (15)	150 (45)	400[j] (120)
Existing	75 (23)	100 (30)	50 (15)	50 (15)	150 (45)	400[j] (120)

BUSINESS						
New	75[k] (23)	100[k] (30)	20 (6.1)	50 (15)	200 (61)	300 (91)
Existing	75[k] (23)	100[k] (30)	50 (15)	50 (15)	200 (61)	300 (91)
INDUSTRIAL						
General	50 (15)	100 (30)	50 (15)	50 (15)	200[l] (61)	250[m] (75)
Special Purpose	50 (15)	100 (30)	50 (15)	50 (15)	300 (91)	400 (122)
High Hazard	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	75 (23)
Aircraft-Servicing Hangars, Ground Floor	50[n] (15)	100[n] (30)	50[n] (15)	50[n] (15)	[a]	[a]
Aircraft-Servicing Hangars, Mezzanine Floor	50[n] (15)	75[n] (23)	50[n] (15)	50[n] (15)	75 (23)	75 (23)
STORAGE						
Low Hazard	NR	NR	NR	NR	NR	NR
Ordinary Hazard	50 (15)	100 (30)	50 (15)	100 (30)	200 (61)	400 (122)
High Hazard	0 (0)	0 (0)	0 (0)	0 (0)	75 (23)	100 (30)
Parking Garages, Open	50 (15)	50 (15)	50 (15)	50 (15)	300 (91)	3400 (122)
Parking Garages, Enclosed	50 (15)	50 (15)	50 (15)	50 (15)	150 (45)	200 (60)
Aircraft Storage Hangars, Ground Floor	50[n] (15)	100[n] (30)	50[n] (15)	50[n] (15)	[a]	[a]
Aircraft-Servicing Hangars, Mezzanine Floor	50[n] (15)	75[n] (23)	50[n] (15)	50[n] (15)	75 (23)	75 (23)
Underground Spaces in Grain Elevators	50[n] (15)	100[n] (30)	50[n] (15)	100[n] (30)	200 (61)	400 (122)

Source: Adapted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, National Fire Protection Association®, Quincy, MA 02169.

[a]For common path serving >50 persons; 75 ft (23 m) for common path serving <50 persons.

[b]Dead-end corridors of 20 ft (6.1 m) permitted; dead-end aisles of 20 ft (6.1 m) permitted.

[c]See Chapters 12 and 13 of NFPA 101 for special considerations for smoke-protected assembly seating in arenas and stadia.

[d]This dimension is for the total travel distance, assuming incremental portions have fully utilized their allowable maximums. For travel distance within the room, and from the room exit access door to the exit, see the appropriate occupancy chapter of NFPA 101.

[e]See business occupancies, Chapter 38 and 39 of NFPA 101.

[f]See Chapter 23 of NFPA 101 for special considerations for existing common paths.

[g]This dimension is from the room/corridor or suite/corridor exit access door to the exit; thus it applies to corridor common path.

[h]See the appropriate occupancy chapter of NFPA 101 for second exit access based on room area.

[i]See appropriate occupancy chapter of NFPA 101 for special travel distance considerations for exterior ways of exit access.

[j]See 36.4.4 and 37.4.4 of NFPA 101 for special travel distance considerations in covered malls considered pedestrian ways.

[k]See Chapters 38 and 39 of NFPA 101 for special common path considerations for single-tenant spaces.

[l]See Chapters 40 and 42 of NFPA 101 for special requirements on spacing of doors in aircraft hangars.

[m]See Chapter 40 of NFPA 101 for industrial occupancy special travel distance considerations.

[n]See Chapters 40 and 42 of NFPA 101 for special requirements if high hazard.

TABLE 25.4 Summary of NFPA 101®: *Life Safety Code®*, Provisions for Occupant Load and Exit Capacity

Occupancy	Occupant Load ft² (m²) per person	Level Components Doors, Corridors, Horizontal Exits, Ramps	Stairs
Assembly			
Less-concentrated use without fixed seating	15 Net (1.4)	0.2	0.3
Concentrated use without fixed seating	7 Net (0.65)	0.2	0.3
Fixed seating	Actual number of seats	0.2	0.3
Educational			
Classrooms	20 Net (1.9)	0.2	0.3
Shops and vocational	50 Net (4.6)	0.2	0.3
Care centers	35 Net (3.3)	0.2	0.3
Health care		NAS AS	NAS AS
Sleeping departments	120 Gross (11.1)	0.5 0.2	0.6 0.3
Treatment departments	240 Gross (22.3)	0.5 0.2	0.6 0.3
Residential	200 Gross (18.6)	0.2	
Board and care	200 Gross (18.6)	0.2	0.3
Mercantile			
Street floor and sales basement	30 Gross (2.8)	0.2	0.3
Multiple street floors (each)	40 Gross (3.7)	0.2	0.3
Other floors	60 Gross (5.6)	0.2	0.3
Storage–shipping	300 Gross (27.9)	0.2	0.3
Malls	See Code	0.2	0.3
Business	100 Gross (9.3)	0.2	0.3
Industrial	100 Gross (9.3)	0.2	0.3
Detention and correctional	120 Gross (11.1)	0.2	0.3

Source: Adapted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, National Fire Protection Association®. Quincy, MA 02169.

NAS = nonsprinklered; AS = sprinklered.

TABLE 25.5 Requirements for Exit Stairs

	New Stairs	Existing Stairs
Minimum width clear of all obstructions[a]:		
Total occupant load[b] = 50 or more	44 in. (1.12 m)	36 in. (0.91 m)
= less than 50	36 in. (0.91 m)	36 in. (0.91 m)
Maximum height of risers	7 in. (178 mm)	8 in. (203 mm)
Minimum height of risers	4 in. (102 mm)	
Minimum tread depth	11 in. (279 mm)	9 in. (229 mm)
Minimum headroom	6 ft 8 in. (2.03 m)	6 ft 8 in. (2.03 m)
Maximum height between landings	12 ft (3.7 m)	12 ft (3.7 m)
Minimum dimension of landings in direction of travel	[c]	[d]
Doors opening immediately on stairs, without a landing at least the width of door	No	No

Source: Adapted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, National Fire Protection Association®, Quincy, MA 02169.

[a]Except projections not exceeding 3½ in. (89 mm) at and below handrail height on each side.

[b]Total occupant load includes all floors served by stairway.

[c]Every landing shall have a dimension, measured in the direction of travel, equal to the width of the stair. Such dimension need not exceed 4 ft (1.22 m) when the stair has a straight run.

[d]Stairways and intermediate landings shall continue with no decrease in width along the direction of exit travel.

are held open at each floor to admit occupants fleeing the fire, smoke can readily enter the stairwell. Moreover, it is becoming increasingly common for people to refuse to evacuate a high-rise building, placing their faith in fire-extinguishing systems instead of facing a daunting descent through many floors of fire stairs.

Because of the impracticality of rapid evacuation, larger buildings are required to provide *refuge areas* where smoke penetration is less likely. For example, stairs can be designed to hold *all* the occupants, in which case the design of discharge is based more on *capacity* than on *flow*. At maximum crowding, about 3 ft^2 (0.28 m^2) per person is recommended. Again, smokeproof towers will be safer in such a design, although stairs can be pressurized with outdoor air. These details related to smoke control are presented in Section 25.2.

(f) Property Protection

One of the earliest design concerns in this category is that the site should permit access for firefighting equipment. Ideally, fire trucks should be able to pull alongside each exterior wall. If accessibility is limited by adjacent buildings, and roadways alongside buildings and other measures are impractical, more reliance must be placed on internal fire-suppression systems. Another factor is the amount of time it will ordinarily take for firefighters to reach a site. In congested urban areas or remote rural ones, the time that elapses between the alarm and the arrival of firefighters can permit a fire to grow to unstoppable proportions. In these cases, emphasis again shifts to internal fire-suppression systems.

Another design concern is adequate water to fight the fire. Reliance on city water mains is not always a good solution. Elevated tanks on buildings can help in the early moments of firefighting, but their capacity is soon exhausted. Some buildings therefore rely on lakes or enclosed reservoirs for a firefighting water supply (see the discussion in Section 25.3).

Exposure protection is becoming common in areas where highly flammable surroundings pose a serious threat of fires originating *outside* a building. Candidates for exposure protection include buildings surrounded by older wooden buildings, bordered by lumberyards or other commercial activities that utilize highly flammable materials, or even bordered by open fields of dry grass or brush. Exposure protection guards against heat transfer by radiation and convective currents and against direct fire transfer via flying embers. Exposure protection begins with the use of nonflammable materials for the building's exterior. Erecting firewalls between the building and a fire-threatening neighbor is a more drastic, but sometimes necessary, step. Exposure protection sometimes includes external water sprinkler systems, in which a spray head is placed over (or under) openings such as windows or doors. Sprinkler systems that soak the roof can play a cooling role on summer days, as well as a fire exposure protection role. Exterior doors can be chosen for their fire-delaying characteristics. Windows can also be protected by fire-rated shutters that are designed to close automatically at high temperatures (Fig. 25.5). Sometimes exterior protection is necessary to protect the *exit discharge* from flames originating *inside* the building, as with narrow alleyways like that in Fig. 25.5 in downtown Pittsburgh.

Fig. 25.5 *Rolling metal shutters, housed in valences above each window, punctuate the exterior of this downtown Pittsburgh building opening onto a narrow street. The shutters can protect the building's contents from an exterior fire, but can also protect the narrow street from a fire inside the building. Note the exterior fire escapes across this narrow street. These are no longer permitted, partly because smoke plumes rising from windows can make such stairs unusable long before heat from a fire becomes a threat.*

Compartmentation has become increasingly important as buildings have become lightweight structures incorporating decreased fire resistance and open floor areas that encourage the spread of fires. Building codes establish maximum floor area limits based upon construction type and occupancy. If a building's floor area exceeds such limits, it must be subdivided by firewalls into areas that fall within the code limitations. Automatic fire sprinklers allow for increased floor area limits, which can be a motivator for including sprinklers in a building context where they are not mandatory.

Openings in firewalls and similar protective constructions must be protected by fire-rated doors. Fire dampers must be installed in HVAC ductwork wherever ducts pass through a fire-rated construction (Fig. 25.6). The intent is to not degrade fire resistance by the inclusion of weaker-link components. As important as compartmentation is in buildings with large floor areas, however, the vertical spread of fire (its natural path) poses a more serious problem. Fire-resistive barriers to limit vertical fire spread are also part of the compartmentation requirements found in codes. Thus, strict requirements to protect vertical openings and pathways are found in the fire codes.

Concealed spaces are found in many contemporary buildings, especially over suspended ceilings but also behind walls, within pipe chases, in attics, under raised floors, and in other places. All such spaces can offer paths for the spread of fire. The designer can utilize noncombustible materials, as far as possible, in such spaces. Another important step is to include automatic fire detection and suppression systems in these uninhabited spaces—and often the use of oxygen-deprivation approaches to fire suppression. Another design response is compartmentation: using firestops (or firewalls) to break up otherwise continuous concealed spaces. Many codes, for example, require firestopping around each 1000 ft^2 (93 m^2) of suspended ceiling area and every 2000 ft^2 (186 m^2) of attic floor area.

Structural protection, another important requirement, allows a building to continue to stand during a fire and enables it to be salvaged rather than demolished after a fire. Codes require various protective layers for structural materials. In order of importance, it is usually most critical to protect columns, girders, beams, and, finally, the floor slab.

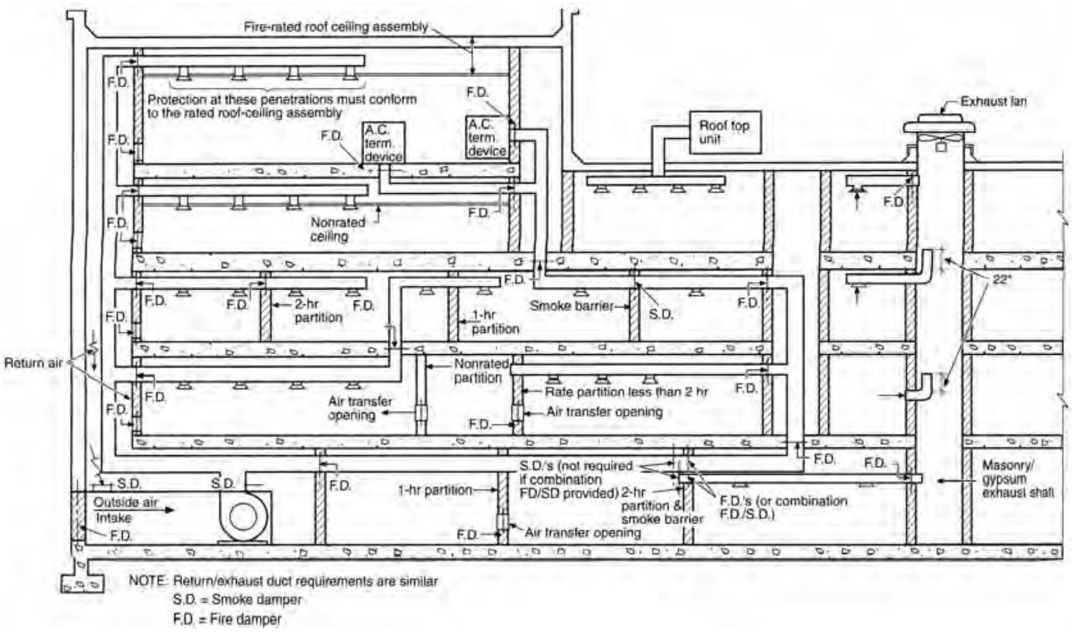


Fig. 25.6 *Locations of fire dampers in a typical ducted HVAC system—at all penetrations through firewalls, fire-rated ceiling/floor assemblies, and vertical chase enclosures. (Reprinted with permission from the* Fire Protection Handbook, *20th ed.; copyright © 2008, National Fire Protection Association®. Quincy, MA 02269.)*

(g) Continuity of Operations

For most building functions, it is desirable to minimize the disruption of operation that a fire will cause. Design strategies to encourage continuity of operations include special fire alarm/suppression systems for especially critical operations areas (control rooms, for example), the design of HVAC systems to allow for 100% outdoor air (to aid in purging a building of smoke), and provision for the speedy removal of the water dumped on a fire by a sprinkler system. The floors in sprinkler-served buildings should be (yet rarely are) waterproof; waterproofing should also be carried up walls, columns, pipes, and other elements to a height of 4 to 6 in. (100 to 150 mm) above the floor. These provisions will help to minimize the water damage associated with fire-suppression efforts.

25.2 SMOKE CONTROL

As experience has made it increasingly evident that smoke kills more people in building fire events than either heat or structural collapse, it has also become the norm to design for smoke control as well as for resistance to fire and for fire suppression. The objectives of smoke control are the same as those for fire resistance: to reduce deaths and property damage due to smoke and provide for continuity of operations with minimal smoke interference. Airflow management systems have been used for several generations; laboratory buildings and commercial kitchens equipped with fume/exhaust hoods offer a familiar example. Several options for smoke control are now readily available for ordinary building design—and required by most building codes.

(a) Factors in Smoke Control

The heat of a fire produces air pressure and buoyancy that aid the spread of smoke well beyond the scene of the fire itself. In low buildings, the smoke is spread primarily by heat-induced convective air motion and by the differential air pressures caused by the expansion of gases as the temperature increases. In tall buildings, the stack effect complicates this pattern of smoke spread, encouraging the rapid rise of heated air within vertical shafts. Wind forces from outside are also more likely to be a factor in tall buildings. (Wind velocities are usually higher with increasing distance from the ground surface.) Forced-air systems, so common in high-rise buildings, can also contribute to the spread of smoke. The interactions among fire, the stack effect, wind, building geometry, and HVAC systems are complex. Several detailed calculation techniques are available, as explained in NFPA 92 (NFPA, 2012). These methods include building and testing a scale model, using a series of closed-form algebraic equations, and modeling a compartment fire with the help of a computer. In the last category, a more modest *zone* approach divides a fire into two zones (upper and lower), and the calculations can be done on a personal computer. The more ambitious *field* approach uses computational fluid dynamics (CFD), requiring greater computer capacity but allowing the testing of numerous variations in approaches to fire and smoke control; fire growth, smoke spread, structural behavior, and occupant evacuation can be examined together. Results can be surprising, leading at times to counterintuitive solutions.

(b) Confinement

A passive design response to smoke migration is to try to confine it to the fire area itself. Another technique is to exclude smoke from specially protected areas, called *refuges*. Compartmentation is important in these approaches: Where firewalls cannot be used, partial smoke barriers (often called *curtain boards*) are suspended from the ceiling (Fig. 25.7) in an effort to trap the initial layer of hot air and smoke, and therefore to set off the fire detection/suppression system more quickly. As useful as these partial barriers can be in a fire's early stages, they quickly lose effectiveness as the smoke layer thickens, or as air pressure forces the smoke below the boards. Even with firewalls with fire-rated doors, small gaps and cracks can provide smoke paths, aided by the air pressure differences that fires can quickly produce. The typical "fire" barrier is not very resistant to spreading smoke, and smoke control based solely on confinement must be closely linked to an effective early detection/suppression technique such as a sprinkler system.

Compartmentation may not always be the best strategy. In the Potomac Mills Mall in

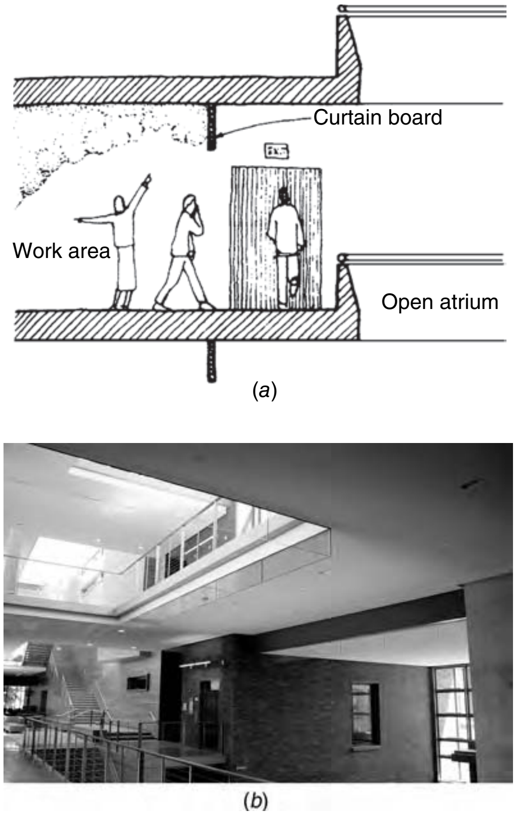


Fig. 25.7 *(a) Smoke barriers (curtain boards) are useful in a fire's early stages. By confining the initial layer of heated air and smoke produced by a fire, they help to slow the spread of smoke while making the early detection and suppression of the fire more likely. (b) Glass used as curtain board in the atrium of the Lewis Integrative Science Building, University of Oregon. (© Ayush Vaidya; used with permission.)*

Prince William County, Virginia, a 156,000-ft^2 (14,493-m^2) addition to the shopping mall uses low walls and a high ceiling. The walls separating tenant spaces and public corridors are 12 ft (3.7 m) high, while the ceiling is at 17 ft (5.2 m), resulting in a large open volume of air. Smoke rising from a fire within a store can certainly spread well beyond that store, but will collect overhead in such a large space that evacuation of the mall can be completed well before the smoke reaches the occupied zone near the floor. A computer model indicated that 20 minutes into a fire (and assuming *no* sprinkler operation), the smoke layer would have dropped to 12.3 ft (3.75 m) above the floor. If the walls were extended to the ceiling, this same building would experience, in the same 20 minutes, within the origin store of the fire, smoke all the way down to the floor. With such a solution, CFD analysis may well be required before approval is granted by the code authority.

(c) Dilution

For a limited time in a fire's early stages, the dilution of smoke with 100% outdoor air (provided by the HVAC system) may make conditions bearable during occupant evacuation. Large quantities of fresh air are needed in so short a time, however, that dilution alone is rarely sufficient for smoke control, particularly when the smoke contains toxic components. When a dilution system is combined with both confinement and early detection/suppression systems, it becomes more feasible and attractive. Dilution systems that dump large quantities of outdoor air into refuge areas (including stairs) can create such high pressures within the refuge that smoke cannot enter through cracks around doors. When, however, doors to the area are opened (as when more people enter the refuge) dilution systems that rely on a conventional HVAC system can rarely provide sufficient pressure to exclude smoke.

Fan-driven dilution systems raise several issues. Is the fan located where fire will not affect its performance and where its air intake can be kept free of smoke? Given the multiple possibilities for building fire locations, this is a difficult promise to make. "Dedicated" systems, independent of the building's HVAC system, are often favored to enable such emergency equipment to be isolated and because such huge quantities of air for relatively small spaces are well beyond the capability of the typical HVAC system. Where should the fresh air supply outlets be located? Most certainly, *below* the level of smoke accumulation so as not to drive smoke downward. (This may suggest using an under-floor air supply distribution system for such a purpose.) In a stair, at what intervals should fresh air be supplied? Some fire engineers say every 3 floors, others say every 10, but supplying all the fresh air from either the top or the bottom is *not* recommended; it is too likely that open doors near a single source location would deplete fresh air for the rest of the stair. At what velocity should fresh air be supplied? The recommended maximum is 200 fpm (1 m/s) to avoid stirring the smoke layer and inviting its descent. The designer must consider that high rates of flow at low velocities will result in very large grilles being required within the space.

(d) Exhaust

Single-purpose smoke exhaust systems that function only in a fire are becoming more common. These systems employ both air velocity and air pressure to help control smoke movement. As with dilution systems, high velocities are avoided so that fresh air is not drawn up through the smoke layer. Such systems are particularly useful in large-volume atrium spaces, as in Fig. 25.8. Smoke accumulating at the ceiling is removed, while fresh air is supplied lower in the space. If smoke can be removed at the same rate at which it is generated, the smoke layer can be kept from descending. Although they involve a greater initial expense, because they require special fans and special smoke-exhaust shafts, such systems have several advantages over simple confinement or dilution approaches:

1. They can help prevent toxic gases from entering refuge areas (particularly when there is a dilution or outdoor air supply to such areas).
2. They can help reduce concentrations of dangerous gases, potentially making conditions somewhat more tenable for those exposed to smoke-affected spaces.
3. By creating desirable patterns of air pressure, they can reduce smoke migration to areas of a building not directly involved with a fire event.
4. With them, the stack effect, complicated by buoyancy and wind, is less likely to overcome the smoke-control system in a tall building.
5. They can help to remove smoke that remains after the fire is extinguished.

Each of the two Petronas Towers in Kuala Lumpur, Malaysia, is occupied by as many as 18,000 workers during the day. These were the tallest buildings in the world at the turn of the twenty-first century, placing a majority of the workers well beyond the range of ordinary fire-rescue operations. Smoke exhaust, stair pressurization, and vestibule pressurization systems are installed, and each floor has isolation dampers, controlled by the fire alarm system, wherever air ducts serve multiple floors. Because each floor has its own air-handling system (using floor-by-floor fan rooms), however, vertical ductwork is minimized. There are both a main and a secondary fire command center for each of the towers and associated lower buildings.

(e) HVAC Systems, Sprinklers, and Smoke

Two systems within a building must be closely coordinated with smoke exhaust systems: the HVAC system and the fire detection/suppression (usually sprinkler) system. As the fire detection system activates the smoke exhaust fans, it must also override the conventional HVAC system operation, usually by switching to 100% outdoor supply air and simultaneously blocking the return air system. This action pressurizes each HVAC zone to form a barrier against smoke (Fig. 25.9) and keeps smoke out of the return duct system. If the HVAC system is variable air volume (VAV), all supply control valves (dampers) must be moved to their full open position. If additional protection is needed for refuge areas, additional air supply to such areas can be provided, perhaps by a separate (smoke dilution) system, as described earlier.

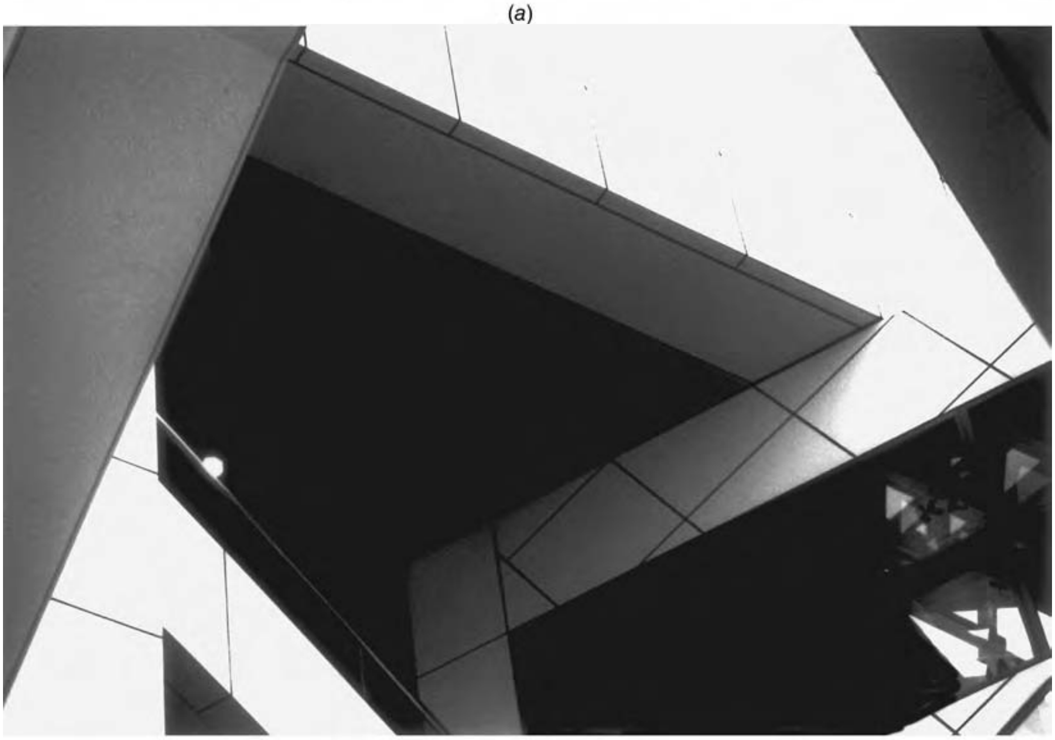
An automatic sprinkler system can reduce the extent of smoke development by quickly extinguishing a fire; conversely, a sprinkler system can affect the functioning of smoke exhaust systems, both by creating a curtain of water that inhibits the movement of smoke and by cooling the smoke, thus reducing its buoyancy. As less buoyant smoke descends, visibility is reduced and the danger of smoke inhalation increases, particularly in spaces with ordinary ceiling heights. The buoyancy of smoke is a key factor in the success of a smoke exhaust shaft, whose intake is located at ceiling level within each zone. Although these two systems may appear to work at cross-purposes, suppression of a fire is as important a goal as smoke control. Sprinkler systems typically suppress fires so quickly that the size of the accompanying smoke exhaust systems can generally be reduced.

When the fire-suppression system relies on oxygen displacement (such as with carbon dioxide or "clean agents"), smoke exhaust systems clearly pose a threat—special attention is required if both systems are to be used. Luckily, oxygen displacement systems are often used in nonhabitable spaces, where smoke evacuation is less of an issue.

(f) Automatic Ventilating Hatches

These heat-and-smoke venting devices (that operate without fans) are required by code in selected occupancies—such as stages and certain warehouse/

(a)



(b)

Fig. 25.8 *The Rock and Roll Hall of Fame and Museum on Cleveland's lakefront (a) features a tall, pyramidal interior space. (b) At the apex, a large horizontal grille marks the smoke exhaust system intake. Smoke naturally accumulates here, and can be removed while dedicated sources of fresh air operate at ground level around the perimeter. (When hot days alternate with cool nights, such a system could be used for night ventilation of thermal mass.)*

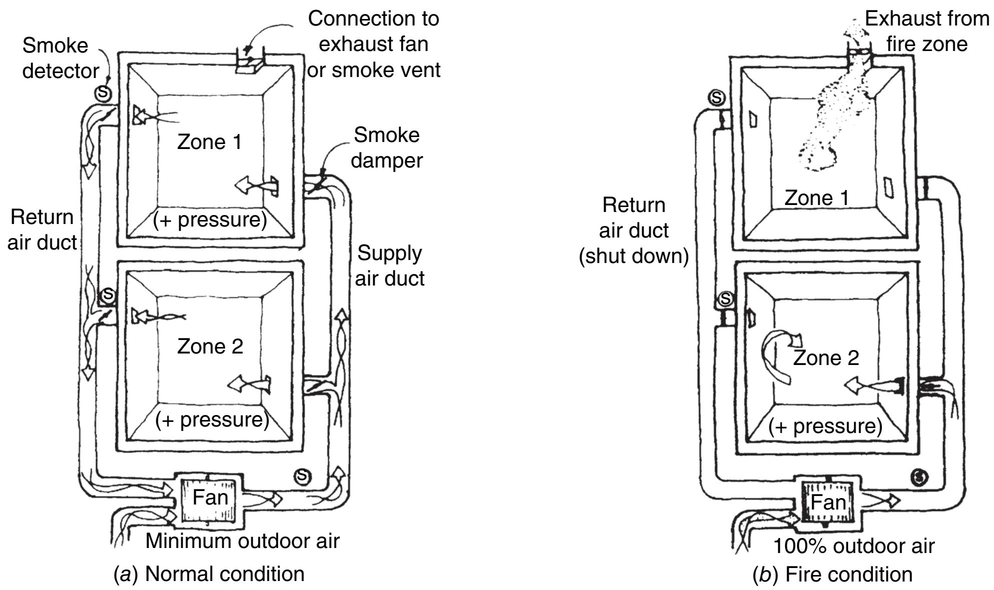


Fig. 25.9 *Smoke control by a smoke exhaust system. (a) The conventional HVAC system is shown operating under normal minimum outdoor air supply conditions. (b) When smoke detectors trigger the smoke exhaust system, dedicated fans begin to exhaust smoke, through a special duct, from the affected area only. Simultaneously, the conventional system undergoes two changes: All supply air becomes 100% outdoor air (for smoke dilution), and all return openings are closed off (to pressurize all nonfire areas, to keep smoke out of them and out of the return duct system).*

storage facilities (ICC 2012a, 2012b). They may also be installed (Fig. 25.10) in other building types as part of an engineered smoke control system. The hatches open individually as heat or smoke from a fire triggers their control devices. As a result, indoor conditions near the fire are improved for firefighters, and firefighters on the roof are quickly alerted to the general location of the fire below.

In summary, designers can provide several components that aid in the exhaust of smoke and the provision of ventilation and improved visibility for firefighters and occupants in almost any building: dedicated smoke exhaust and dilution systems, emergency controls on HVAC systems, operable windows and skylights (to facilitate ventilation and occupant escape), and heat-and-smoke hatches in roofs.

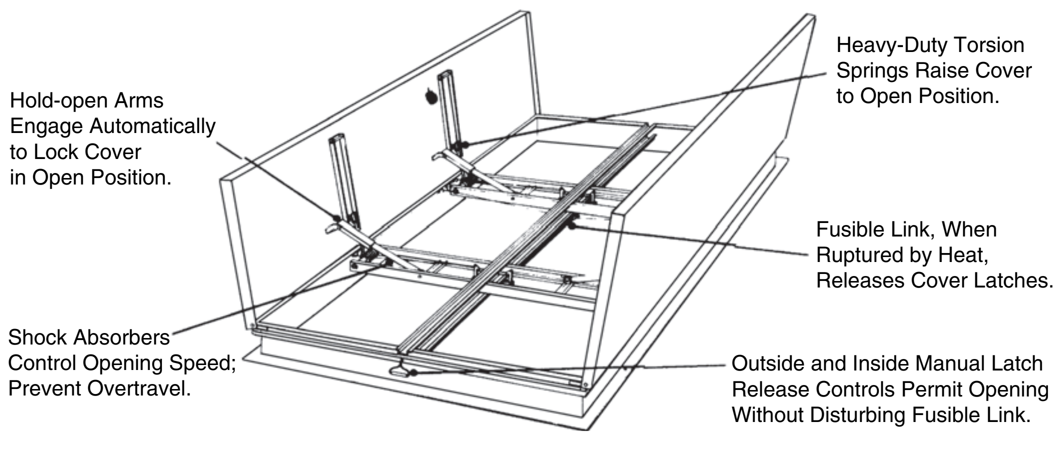


Fig. 25.10 *Automatic heat-and-smoke roof hatch ventilators, primarily for one-story commercial and industrial buildings. (Courtesy of Inryco, Inc.)*

25.3 WATER FOR FIRE SUPPRESSION

The most popular medium for building fire suppression is water, which is readily available and relatively low in cost. Water cools, smothers, emulsifies, and dilutes. As it turns to vapor, it removes 970 Btu/lb of water (2256 kJ/kg) at atmospheric pressure, and its volume increases 1700 times—a process that hinders access to the oxygen needed by the fire. Water has several disadvantages that sometimes preclude its use for fire suppression: It damages most building contents, including interior surfaces; as a stream, it conducts electricity readily (less readily as a spray); and many flammable oils will float on water while continuing to burn. Where these factors are major considerations, other suppression media can be considered (see Section 25.4).

Fire-suppressing systems are commonly combined with smoke control systems; Figure 25.11 shows a typical combination of provisions in a one-story building. Taller buildings, especially those with multistory interior spaces (atria), present a special challenge (Fig. 25.12). A typical approach is to construct an approximately 6-ft- (1.8-m-) deep curtain

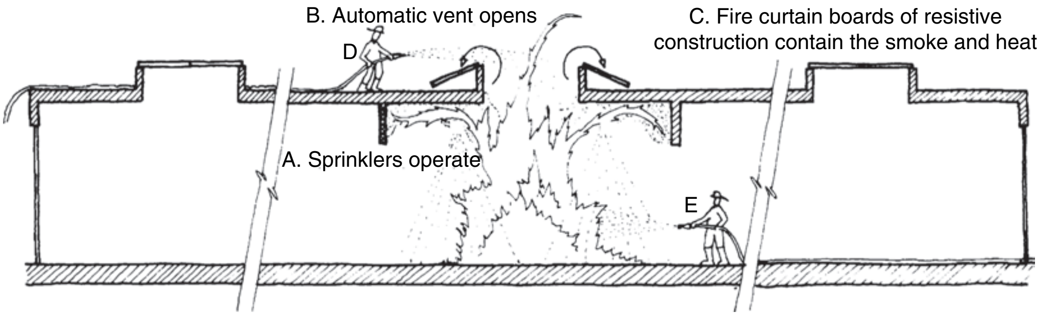


Fig. 25.11 *Fire protection for large-area, one-story buildings showing the fire suppression (sprinkler) system (A) and the smoke control system (B, C). Locations D and E are relatively safe positions for firefighters.*

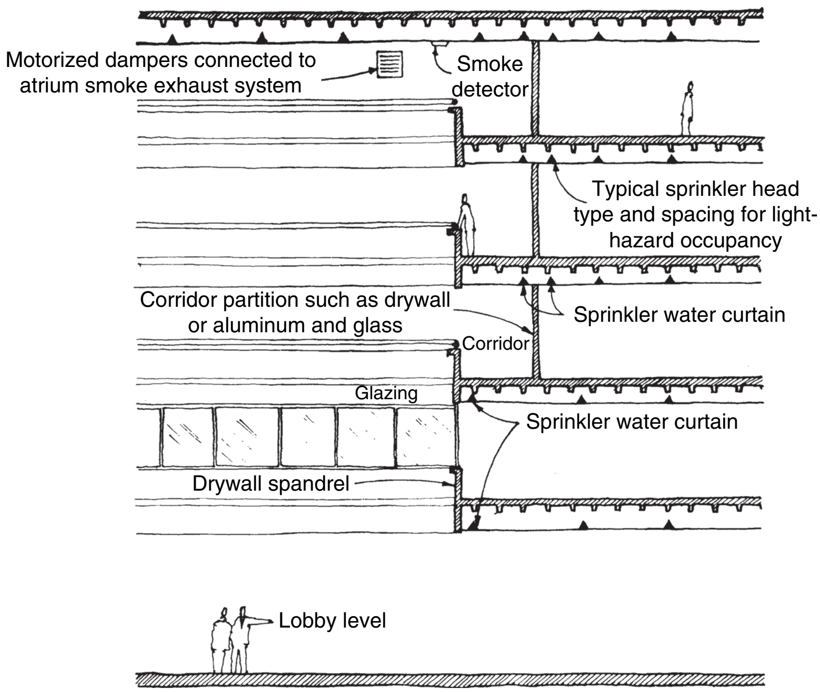


Fig. 25.12 *Fire protection in an atrium-type office building: section showing the detection/suppression system and provisions for smoke control.*

board (or fire spandrel) at the opening to the atrium on each floor. Smoke detectors, motorized dampers, and sprinklers can be combined in various ways. At the lobby level, the atrium floor level, and at any office floors open to the atrium, sprinklers at about 6 ft (1.8 m) o.c. (on center) will provide a water curtain at the edge of the atrium opening. Where glazing is used at the atrium's perimeter, the glazing frames sometimes can be designed for considerable thermal expansion, and sprinklers can provide a water curtain on the office side of the glazing. Fire-rated glazings and their frames are listed for both heat resistance and water pressure from a hose stream. Where balcony corridors adjoin the atrium, two sprinkler water curtains can be provided, one on either side of the partitions between corridor and office space. The smoke exhaust system often can provide six air changes per hour (ACH) for all spaces that open onto the atrium.

(a) Standpipes and Hoses

Standpipes and hoses (Fig. 25.13) with a separate water reserve, upfeed pumping, and/or fire department connections are listed in three classes and five types. The major differences are whether the system is for first-aid or full-scale firefighting and whether the system has an automatic water supply or a manual one.

Class I systems are for full-scale firefighting, and are typically required in both sprinklered and unsprinklered buildings more than three stories high, as well as in malls. (This requirement is based on the substantial time required to lay out hoses from outdoor fire connections in such buildings.) This system is for use by trained firefighters using 2½-in. (64-mm) hose connections at designated locations. Class I is becoming the system of choice as use of the next two system types declines.

Class II systems are for first-aid firefighting before the fire trucks arrive. These systems use 1½-in. (38-mm) hose connections and typically provide access to a hose, nozzle, and hose rack (Fig. 25.14) in each specified location. The difficulty

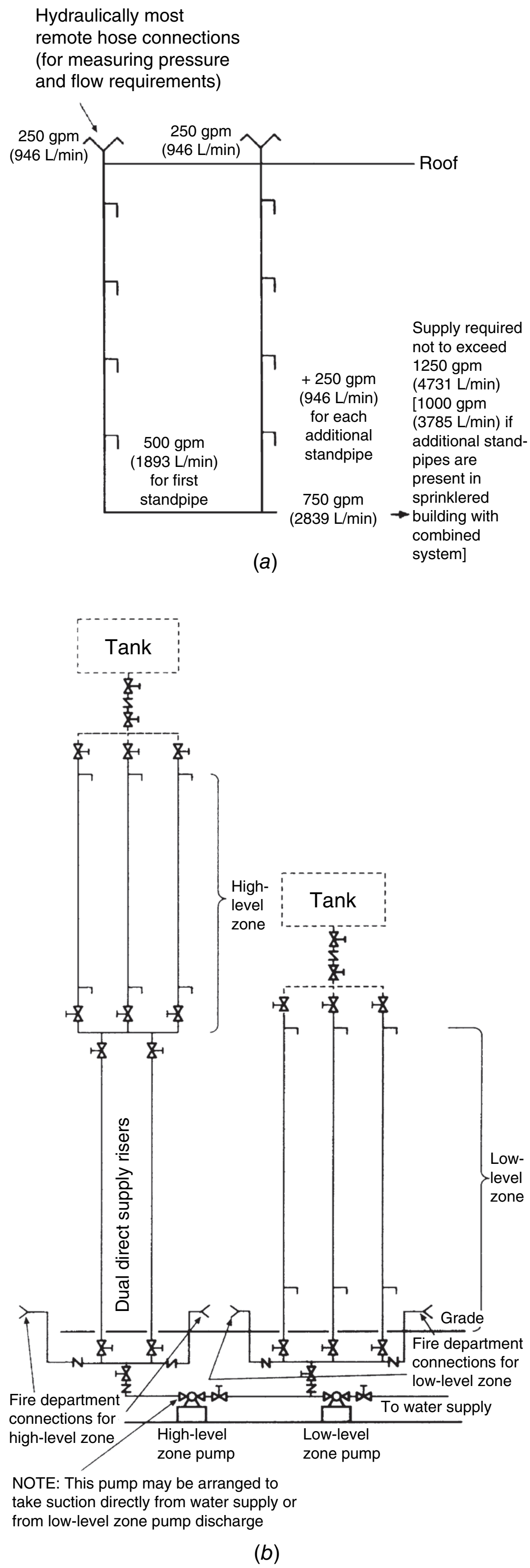


Fig. 25.13 *Standpipe system variations. (a) Basic flow rate requirements for Class I and Class III systems. (b) Multiple-zone system. (Reprinted with permission from the* Fire Protection Handbook, *20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269.)*

(*a*)

(*b*)

(*c*)

Fig. 25.14 *Components of a standpipe and hose system. (a) Standard hose rack. (b) Hose rack and fire extinguisher in a cabinet with a glass door. (c) Siamese connection through which fire department pumping equipment supplies water to the standpipe system. The similar sprinkler siamese is marked "sprinkler." Color codes sometimes differentiate the two.*

experienced by untrained people trying to manage a 100-ft (30-m) hose containing a huge flow (100 gpm [378 L/min] or more) has led to a decline in the use of this system, although it can be found in large unsprinklered buildings and in special hazard areas such as stages. Many fire departments would rather the building occupants evacuate than try to manage such large hoses and water quantities. Significant water damage is a potential threat when hoses cannot be controlled.

Class III systems combine the characteristics of Classes I and II, thus serving both for first-aid and for full-scale firefighting. Hose connections of both sizes are provided (with adapters) at each specified location. The disadvantages of Class II systems also apply to Class III, and their use is declining for the same reasons.

"*Combined*" systems are either Class I or III standpipe systems that also supply water to a sprinkler system.

The standpipe system types are as follows:

Automatic-wet systems. The pipes are filled with water and are connected to a water supply capable of automatically meeting the firefighting demands. Water flows immediately upon opening of a hose valve.

Automatic-dry systems. The pipes are filled with pressurized air, and are connected to a water supply capable of automatically meeting the firefighting demands. Through a device such as a dry-pipe valve, water replaces the air when a hose valve is opened.

Semiautomatic-dry systems. The pipes are filled with air and are connected to a water supply capable of automatically meeting the firefighting demands. Through a device such as a deluge valve, water replaces the air when both a remote sensing device at the hose station and a hose valve are opened.

Manual-dry systems. The pipes are filled with air, and there is no connection to a water supply system other than that provided by the fire department (as in Fig. 25.14*c*).

Manual-wet systems. The pipes are filled with water, with a connection to a domestic water source that is used merely to fill and test the system. Water for firefighting is provided by the fire department.

Minimum flow rates and minimum and maximum pressure are all addressed during the design of standpipe systems. Two methods of sizing, the pipe schedule and the hydraulic method, are used. Neither is detailed here; see NFPA 14 (NFPA, 2013) for the procedures. The required supply flow rates are outlined in Fig. 25.13*a*. As a preliminary design guideline (Fig. 25.13*b*), Class I and III standpipes not exceeding 100 ft (30 m) in height must be a minimum of 4 in. (102 mm) nominal pipe size. Class I and III standpipes more than 100 ft (30 m) in height must be a minimum of 6 in. (152 mm) nominal pipe size (although the topmost 100 ft [30 m] may be a minimum of 4 in. [102 mm] nominal pipe size). For combined standpipe and sprinkler systems, regardless of height, a minimum of 6 in. (152 mm) nominal pipe size is required.

For Class I and III systems, a minimum hose pressure of 100 psi (690 kPa) is now required because of the widespread use of fog nozzles (rather than stream nozzles). The maximum hose pressure (also the maximum for sprinklers) is 175 psi (1207 kPa).

Water supply systems for firefighting may use roof tanks or fire pumps. It is not practical to store enough water on the roof for a protracted firefighting period, and it is usually assumed that a half-hour supply will be more than enough to provide for the time it takes the fire engines to arrive. When the system is used by the fire department, its pumps are attached to the street siamese (Fig. 25.14*c*) to deliver water from street hydrants or the building's "secondary source." The check valve closest to the siamese in use opens, and the check valves at the tank close to prevent the water from rising uselessly in the tank. After the engines are disconnected from the siamese, the water between the siamese and the adjacent check valve drains out through a ball drip so that it does not freeze.

An overhead tank is considered a most dependable source, but the height required can be architecturally undesirable and a considerable structural disadvantage. In such a case, upfeed fire pumps (Fig. 25.13*b*) operating automatically to deliver water to higher stories may be used. Another option in this case is a pneumatic tank that delivers water using the pressure of the air that is compressed in the upper portion of the tank.

A standpipe zone in a high-rise building is determined by hydraulic calculation so that maximum hose pressures are not exceeded. Fire standpipes and their hoses (for full-scale firefighting) are now recommended to be located on the landings of fire stairs, from which personnel or firefighters can approach a fire with charged hoses. This enables the hose connection to be made in a safe (relatively smoke-free) place, half a floor below the fire. Awkwardly, it means that the door to the stair will be held open by the hose, but the risk to occupants using the stairs is considered to be outweighed by the advantage to the firefighters.

(b) Sprinkler System Design Impacts

Unlike a fire hose, a sprinkler is likely to be already positioned above the point of a fire and is capable of deploying in seconds, not minutes. Sprinkler systems are widely relied on as proven automatic fire suppressers. (They have come a very long way from the early water-filled bucket suspended by a black powder fuse; when the fuse was lit by a fire, it blew up the bucket, dispersing the water and theoretically dousing the fire.)

However, designers must remember that the use of sprinklers does *not* give one a license to ignore fire code limitations, even though many codes provide more leeway for sprinklered buildings. In addition, provision must be made for an adequate water supply, adequate water pressure, and backup power for pumping (if pumps are required). It may be wise to provide for water drainage during and after a fire, particularly in multistory buildings. A sprinkler system may require large supply pipes and valves, fire pumps, and access for system monitoring and maintenance. These elements are generally considered unsightly and must be integrated into the architectural design. Sprinklers can afford opportunities for integration with energy-conserving HVAC systems (Section 25.3*k*). Also, the cost of a sprinkler system installation can usually be recovered rather quickly through reductions in fire insurance premiums.

Automatic sprinkler systems usually consist of a horizontal pattern of pipes placed just below or within the ceilings of industrial buildings, warehouses, stores, theaters, offices, homes, and other structures at risk from fire. These pipes are provided with sprinkler heads constructed such that abnormally high temperatures will cause them to open automatically and emit a fine water spray. NFPA 13 (NFPA, 2013) lists the detailed requirements for sprinkler systems (briefly referred to here), as well as numerous other regulations. In addition to pipes and sprinklers (discussed in the remainder of this section), several other system components are usually included.

Alarm Gong. An alarm gong mounted on the outside of the building warns of water flow through the alarm valve upon activation of a sprinkler head. This warning gives the building personnel an opportunity to make additional firefighting arrangements that can minimize loss and speed the termination of the fire; in this way, the sprinklers can be turned off in a timely manner to prevent excessive water damage to building contents after the fire is out. Sprinkler alarms commonly are also connected to private regional supervisory offices that communicate promptly with municipal fire departments upon receipt of a signal. All public buildings, and other buildings as required, should be provided with fire detection and alarm systems that indicate, in the custodian's office, the location of the fire.

Siamese Connections. Siamese connections permit fire engines to pump into the sprinkler system in a manner similar to that used for standpipe systems (Fig. 25.14*c*).

Provisions for Drainage. Sprinkler heads can release a great deal of water, most of which will remain unvaporized and quickly collect at floor level. In addition to waterproofing the floors and lower walls, columns, and other elements, provision should be made, where possible, for gravity drainage of water. Scuppers in exterior walls are preferable to floor drains, which are more easily clogged by debris. Scuppers are provided with hoods that protect against infiltration, birds, and/or insects.

Water Supply. In tall buildings, sprinklers (and standpipes) can be supplied with water from elevated storage tanks used for domestic water. These tanks supply a constant pressure on the distribution lines, store sufficient water to balance supply and demand, prevent excessive starting and stopping of a fire pump, and provide a dependable fire reserve. The last factor has been critical in the calculation of fire insurance rates. When gravity tanks are used with sprinkler systems, they should provide enough water to operate 25% of the sprinkler heads for 20 minutes. As in the case of standpipe and hose systems, this provision gives the fire department a chance to arrive and take over.

The principal objections to the use of tanks have been their unsightliness, the problem of freezing, and—in the case of large buildings—the tanks' tremendous weight, with resulting added structural costs.

Skidmore, Owings & Merrill, in their design for General Mills' central office building in suburban Minneapolis, turned to automatically controlled pumping systems instead of elevated storage (Fig. 25.15). For the General Mills building, the fire underwriters could have required at least 50,000 gal (189,250 L) of residual water in the tank for emergency purposes, which would have meant about 100,000 gal (378,500 L) of elevated storage. The alternative chosen was a reinforced-concrete structure placed underground to one side of the building and covered with 3 to 5 ft (0.9 to 1.5 m) of earth. Small vents rising from this reservoir blend in with the lawn and landscaped shrubbery above.

The saving in structural steel tended to make the overall cost comparable to that of an elevated tank of the same capacity. The savings were made possible chiefly by refined automatic-pump control. The underground reservoir eliminates the problems of an unsightly appearance and great weight, but the other usual advantages of an elevated tank—reliability in case of fire, minimum starting and stopping of motors, and the maintenance of pressure while balancing supply and demand—must be equaled in the automatic-pump control circuitry. This is not as simple as it might at first seem. Factors such as fluctuations in demand, friction within the pipes, elevations, starting surges from the pumps, and pressure-flow characteristics of the pumps themselves must be considered. Various

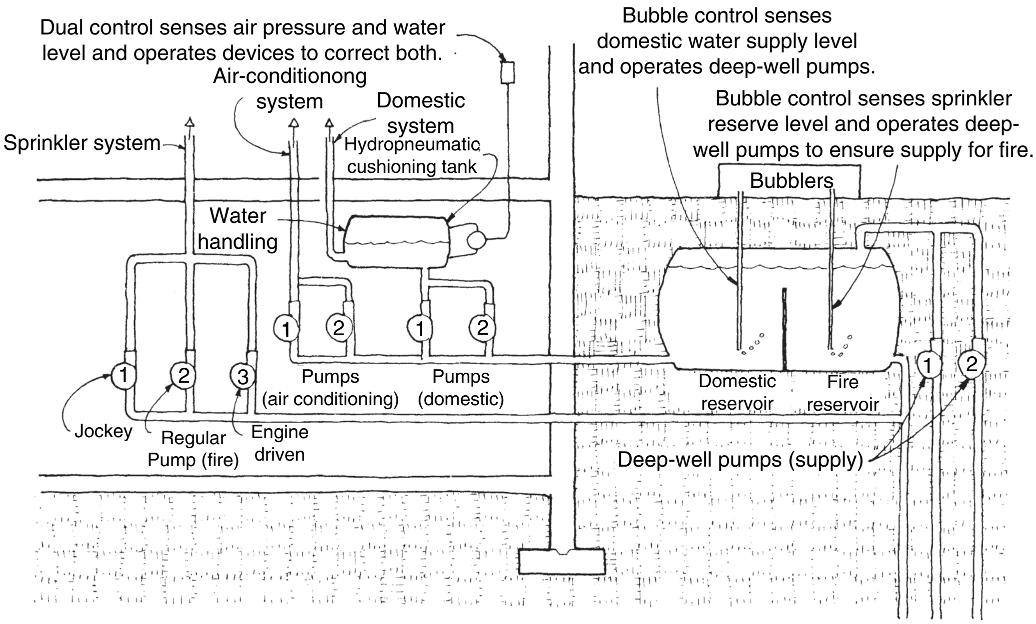


Fig. 25.15 *Diagram of an upfeed pumping system to supply sprinklers and building demands for domestic water. In the General Mills Building, a large subsurface concrete water tank provides a secondary water source that reassures fire insurance carriers. Thus, the wells and their pumps constitute a primary water source. If the well yield fails, the concrete tank supply can be tapped. Backup engine-driven pumping operates in the event of a utility company power outage. Automatic controls and piping for the storage tank reserve system are not shown in this illustration.*

combinations of these issues undoubtedly account for the continued use of elevated tanks. The trend, however, is toward the use of more sophisticated pump control.

A continuous flow from the General Mills deep-well pumps through both domestic and fire reservoirs prevents the water from becoming stale and rancid. The fire reservoir is given necessary priority over the domestic reservoir by means of a simple weir. Even if the domestic reservoir were completely empty, the fire reservoir would remain full. Pressure for the sprinklers is supplied by a small 20-gpm (1.26-L/s) jockey pump. Signals from the sprinkler system bring in a 750-gpm (47.3-L/s) main pump. If this fails, a diesel engine–driven pump of equal capacity automatically takes over. Normally, the system satisfies the heavy demands of air conditioning, fire control, and domestic water supply in this modern, rural, isolated office building.

Valves. Valves are required to allow the sprinkler system to be shut off for maintenance, system modification, or replacement of sprinkler heads that have operated after a fire. Indicating valves of various types are required so that it is always immediately obvious whether such crucial valves are open (as they nearly always should be) or closed. Table 25.6 lists common failure modes in sprinkler systems; an improperly closed valve is the leading reason for system failure.

(c) Sprinkler Construction, Orientation, and Rating

The common sprinkler head blocks water flow by a plug or cap that is held tightly against the orifice by levers or other restraining devices. These, in turn, are held in place by the arms of the sprinkler body. In the past, the restraining device was usually a fusible metal link that melted at a predetermined temperature. Today, the restraining device is typically a glass bulb that contains both a colored liquid and an air bubble. As the liquid expands due to increasing temperature resulting from the heat of a fire, it compresses the air bubble until it is absorbed. Then continued expansion ruptures the bulb (again, at a predetermined temperature) and releases the water in a solid stream through the orifice.

TABLE 25.6 Common Failure Modes for Automatic Sprinklers

Failure Mode	Potential Causes
Water supply valves are closed when sprinkler fuses	Inadequate valve supervision Owner attitude Maintenance policies
Water does not reach sprinkler	Dry pipe accelerator or exhauster malfunctions Pre-action system malfunctions Maintenance and inspection inadequate
Nozzle fails to open when expected	Fire rate of growth too fast Response time and/or temperature of link inappropriate for the area protected Sprinkler link protected from heat Sprinkler link painted, taped, bagged, or corroded Sprinkler skipping
Water cannot contact fuel (*Note:* The intent of this failure mode is to ensure that discharge is not interrupted in a manner that will prevent fire control by a sprinkler)	Fuel is protected High piled storage is present New construction (walls, ductwork, ceilings) obstructs water spray
Water discharge density is not sufficient	Discharge needs are insufficient for the type of fire and the rate of heat release Change in combustible contents occurred Number of sprinklers open is too great for the water supply Water pressure too low Water droplet size is inappropriate for the fire size
Enough water does not continue to flow	Water supply is inadequate because of original deficiencies, changes in water supply, or changes in the combustible contents Pumps are inadequate or unreliable Power supply malfunctions System is disrupted

Source: Reprinted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, by the National Fire Protection Association®, Quincy, MA 02169.

A deflector converts this solid stream of water into a spray, whose pattern is determined by the design of the deflector. Most sprinklers direct the spray down and horizontally rather than upward toward the ceiling. This yields better water distribution close to the sprinkler head and more effective coverage of burning material below. The spray pattern from a typical upright or pendant sprinkler is shown in Fig. 25.16.

Common types of sprinkler heads are upright (SSU), pendant (SSP), or sidewall types. Upright heads sit on top of the exposed supply piping. Pendant heads hang below the piping, which can then be concealed above suspended ceilings (Figs. 25.17*b*, *c*). The pendant heads themselves have a number of variations: Recessed, flush, concealed, and ornamental pendant heads are available (Fig. 25.17*c*). Recessed heads have part of the sprinkler body and the deflector below the ceiling. Flush heads have only the thermosensitive element projecting below the ceiling. Concealed heads are entirely above a ceiling cover plate that falls away in a fire, exposing the thermosensitive element. Ornamental pendants are manufacturer-coated (never field-coated!) to match a desired decor.

Sidewall sprinklers (Fig. 25.17*d*) are usually located adjacent to one wall of a smaller room—common in hotels, apartments, and so on—and throw a one-quarter-sphere spray of water entirely across such rooms. Typically, only one sidewall sprinkler head per small room is used.

The temperature at which a sprinkler is triggered is usually specified, as in Table 25.7. It should be at least 25F° (14C°) higher than the maximum ceiling temperature ordinarily expected. Ordinary sprinkler heads operate at between 135° and 170°F (57° and 77°C).

Buildings to be protected by sprinkler systems fall into several hazard groups, as described in Table 25.8. Newer *quick-response* sprinkler heads are now required throughout light hazard occupancies, including office buildings. These more thermally sensitive heads open sooner than ordinary heads, and thus tend to fight a fire with even

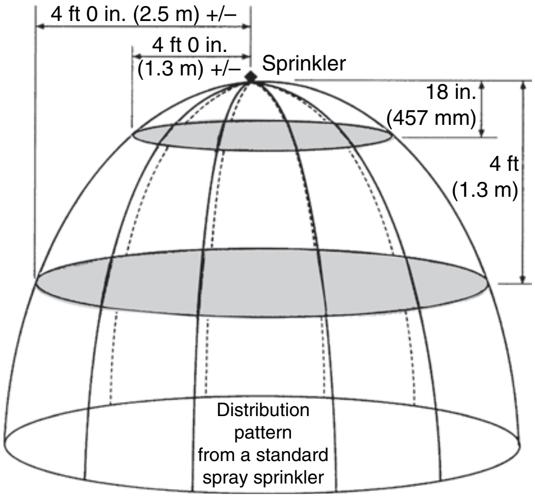


Fig. 25.16 *Typical distribution pattern from a standard spray sprinkler. Obstructions (whether from structure or furnishings) are to be avoided within this volume. (Reprinted with permission from NFPA® 13:* Standard for the Installation of Sprinkler Systems*; © 2012 National Fire Protection Association®. all rights reserved.)*

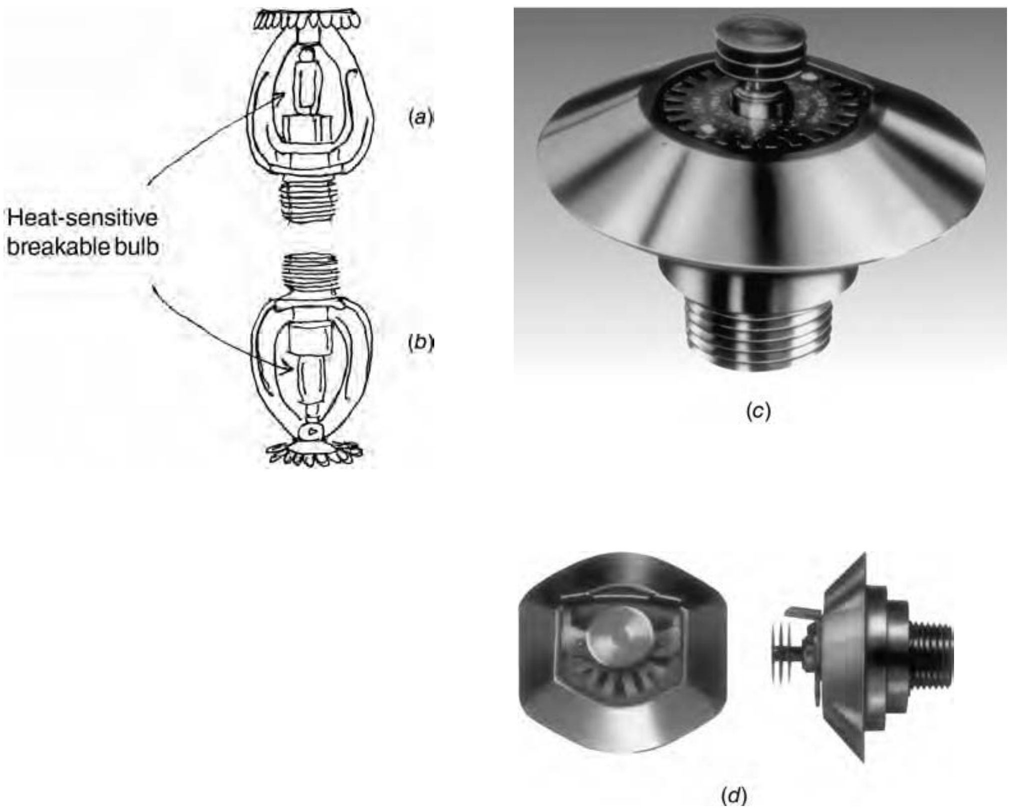


Fig. 25.17 *Sprinkler heads. (a) Upright; it sits above exposed piping, just below the structural deck—where the hottest gases will first accumulate. (b) Pendant, projecting through a suspended ceiling in most installations. Both (a) and (b) use a quartzoid bulb, a transparent bulb with a colored liquid that ruptures at a preset temperature to release the water stream; heads can be manufactured as plated, polished, or colored—but never painted on site. (c) Pendant, styled for a more contemporary appearance. (d) Sidewall, front and side views. (Parts* c and d *courtesy of the Central Sprinkler Corporation.)*

TABLE 25.7 Sprinkler Heads

DISCHARGE CHARACTERISTICS				
Nominal Orifice Size				
in.	**mm**	***K* Factor**	**Nominal Orifice Size Marked on Frame**	**Percent of Nominal ½-in. Discharge**
¼	6.4	1.3–1.5	Yes	25
5/16	8.0	1.8–2.0	Yes	33.3
⅜	9.5	2.6–2.9	Yes	50
7/16	11.0	4.0–4.4	Yes	75
½	12.7	5.3–5.8	No	100
17/32	13.5	7.4–8.2	No	140
⅝	15.9	11.0–11.5	Yes	200
¾	19.0	13.5–14.5	Yes	250

TEMPERATURE CLASSIFICATIONS						
Max. Ceiling Temp.		***Temperature Rating***				
°F	**°C**	**°F**	**°C**	**Temperature Classification**	**Color Code**	**Glass Bulb Colors**
100	38	135 to 170	57 to 77	Ordinary	Uncolored or black	Orange or red
150	66	175 to 225	79 to 107	Intermediate	White	Yellow or green
225	107	250 to 300	121 to 149	High	Blue	Blue
300	149	325 to 375	163 to 191	Extra high	Red	Purple
375	191	400 to 475	204 to 246	Very extra high	Green	Black
475	246	500 to 575	260 to 302	Ultra high	Orange	Black
625	329	650	343	Ultra high	Orange	Black

Source: Reprinted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, National Fire Protection Association®, Quincy, MA 02169.

TABLE 25.8 Relative Fire Hazard for Various Occupancies, as Related to Sprinkler Installations

CLASSIFICATION OF OCCUPANCIES	
Occupancy classifications for this standard relate to sprinkler installations and their water supplies only. They are not intended to be a general classification of occupancy hazards. Examples in the listings below are intended to represent the norm for those occupancy types. Unusual or abnormal fuel loadings or combustible characteristics and susceptibility for changes in these characteristics, for a particular occupancy, are considerations that should be weighed in the selection and classification.	
LIGHT HAZARD OCCUPANCIES	
Occupancies or portions of other occupancies where the quantity and/or combustibility of contents is low, and fires with relatively low rates of heat release are expected.	
The Light Hazard classification is intended to encompass residential occupancies; however, this is not intended to preclude the use of listed sprinklers in residential occupancies or residential portions of other occupancies.	
Light Hazard Occupancies Include Occupancies Having Conditions Similar to:	
Churches	Museums
Clubs	Nursing or convalescent homes
Eaves and overhangs[a]	Office, including data processing
Educational	Residential
Hospitals	Restaurant seating areas
Institutional	Theaters and auditoriums, excluding stages and prosceniums
Libraries (except large stack rooms)	Unused attics
[a]If combustible construction with no combustibles beneath.	

TABLE 25.8 (*Continued*)

ORDINARY HAZARD OCCUPANCIES	
Group 1: Occupancies or portions of other occupancies where combustibility is low, quantity of combustibles is moderate, stockpiles of combustibles do not exceed 8 ft (2.4 m), and fires with moderate rates of heat release are expected.	
Ordinary Hazard Occupancies (Group 1) Include Occupancies Having Conditions Similar to:	
Automobile parking and showrooms	Electronics plants
Bakeries	Glass and glass product manufacturing
Beverage manufacturing	Laundries
Canneries	Restaurant service areas
Dairy products manufacturing and processing	
Group 2: Occupancies or portions of other occupancies where quantity and combustibility of contents is moderate to high, stockpiles do not exceed 12 ft (3.7 m), and fires with moderate to high rates of heat release are expected.	
Ordinary Hazard Occupancies (Group 2) Include Occupancies Having Conditions Similar to:	
Cereal mills	Paper and pulp mills
Chemical plants—ordinary	Paper process plants
Confectionery products	Piers and wharves
Distilleries	Post offices
Dry cleaners	Printing and publishing
Feed mills	Repair garages
Horse stables	Stages
Leather goods manufacturing	Textile manufacturing
Libraries—large stack areas	Tire manufacturing
Machine shops	Tobacco products manufacturing
Metal working	Wood machining
Mercantile	Wood product assembly
EXTRA HAZARD OCCUPANCIES	
Occupancies or portions of other occupancies where quantity and combustibility of contents is very high and flammable and combustible liquids, dust, lint, or other materials are present, introducing the possibility of rapidly developing fires with high rates of heat release. Extra hazard occupancies involve a wide range of variables that may produce severe fires. Extra Hazard Occupancies (Group 1) include occupancies with little or no flammable or combustible liquids.	
Extra Hazard Occupancies (Group 2) include occupancies with moderate to substantial amounts of flammable or combustible liquids or where shielding of combustibles is extensive.	
Extra Hazard Occupancies (Group 1) Include Occupancies Having Conditions Similar to:	
Aircraft hangars[b]	Printing using inks having flash points below 100°F (37.9°C)
Combustible hydraulic fluid use areas	Rubber reclaiming, compounding, drying, milling, vulcanizing
Die casting	Saw mills
Metal extruding	Textile picking, opening, blending, garnetting, carding, combining of cotton, synthetics, wool shoddy, or burlap
Plywood and particle board manufacturing	Upholstering with plastic foams
Extra Hazard Occupancies (Group 2) Include Occupancies Having Conditions Similar to:	
Asphalt saturating	Open oil quenching
Flammable liquids spraying	Plastics processing
Flow coating	Solvent cleaning
Manufactured home or modular building assemblies[c]	Varnish and paint dipping
[b]Except as governed by NFPA 409. [c]Where finished enclosure is present and has combustible interiors.	
SPECIAL OCCUPANCY HAZARDS	
See NFPA 13 for a listing of standards by occupancy.	

Source: Adapted with permission from NFPA 13: *Standard for the Installation of Sprinkler Systems*; © 2012 National Fire Protection Association®. all rights reserved. This reprinted material is not the complete and official position of the National Fire Protection Association on the referenced subject, which is represented only by the standard in its entirety.

fewer heads operating, even though they may sometimes open with extraordinary heat that is not fire-associated. They are considered superior for life protection because of their earlier operation.

Other special sprinkler models include an *extra large orifice* (for delivering large water quantities where water pressures are relatively low) and *multilevel* sprinklers (for use where other sprinklers are at a higher plane within the same space). The lower sprinklers may otherwise have their action retarded by water from the higher-elevation heads.

(d) Sprinkler Spacing and Hazard

The spacing of sprinkler heads and the sizing of supply pipes are complex matters, and most sprinkler systems are designed by professionals working for sprinkler manufacturers. However, some guidelines for preliminary sprinkler location are included here. The first consideration is the degree of hazard faced by the occupants, as listed in Table 25.8. Once this is known, sprinklers and pipes can be approximately located in plan view with the aid of Table 25.9. Maximum floor areas (per floor) to be protected by any single sprinkler system are shown, again by hazard, in Table 25.10. Within each space, sprinklers should be located so as to detect a fire readily and to discharge water over the greatest area (considering obstacles such as joists and beams, partial height partitions, etc.; see Fig. 25.16).

Piping for the sprinkler supply can be hydraulically designed, using fundamental water flow principles. A complicating factor is the expectation that only a small percentage of the sprinklers will actually open; more than 50% of the fires studied over a 49-year period were extinguished by two or fewer sprinklers. A detailed sizing procedure would consider both the available pressure at the highest sprinkler and the expected flow rate, which can vary from 150 to 25,000 gpm (10 to 158 L/s). The sprinklers' actual performance is determined by

$$Q = K\sqrt{p}$$

Where

Q = flow rate, gpm

K = K factor, published for each sprinkler head by U.S. manufacturers (see Table 25.7)

p = pressure, psi

In SI units:

Q = flow rate, L/min

K = K factor (14.3 × I-P K factor)

p = pressure in bars

Sprinkler systems are usually designed for a maximum working pressure of 175 psi (1206 kPa). As a preliminary design guideline:

Light hazard systems need a minimum residual pressure of 15 psi (104 kPa) and 500–750 gpm (32–47 L/s) at the base of the system riser for 30 to 60 minutes.

Ordinary hazard systems need a minimum residual pressure of 20 psi (138 kPa) and 850–1500 gpm (54–95 L/s) at the base of the system riser for 60 to 90 minutes.

In the past, the *pipe schedule* design method made system layout and sizing fairly simple. Now there are requirements for more complicated hydraulically designed systems, which are beyond the scope of this book.

(e) Residential Sprinklers

Now that some building codes require sprinklers in all residential occupancies, some new issues arise. The residential sprinkler is a fast-response device with a tested ability to enhance survivability in the room of fire origin and is thus listed for protection of dwelling units. It is sensitive to both smoldering and rapidly developing fires, opening quickly to fight a fire with only one or two heads operating. This is important because residences normally do not have a water supply with sufficient capacity for standard sprinkler systems. Toxic gases and smoke quickly fill the small rooms typical of residences; a fast response is important for life safety.

Most codes that otherwise require residential sprinklers in all areas make an exception for bathrooms no larger than 55 ft^2 (5.1 m^2); for closets with the least dimension not exceeding 3 ft (0.9 m); for open porches, garages, and carports; for uninhabited attics and crawl spaces (if not used for storage); and for entrance foyers that are not the sole means of egress.

Residential sprinklers also have a special water distribution pattern capable of delivering water to

TABLE 25.9 Protected Area, Maximum Spacing, and Distances below Ceiling for Sprinklers

PART A. UPRIGHT (SSU) AND PENDANT (SSP) SPRINKLERS

	Light Hazard		*Ordinary Hazard*		*Extra Hazard*		*High-Piled Storage*	
Construction Type	**Protection Area, ft^2 (m^2)**	**Spacing (max.), ft (m)**	**Protection Area, ft^2 (m^2)**	**Spacing (max.), ft (m)**	**Protection Area, ft^2 (m^2)**	**Spacing (max.), ft (m)**	**Protection Area, ft^2 (m^2)**	**Spacing (max.), ft (m)**
Noncombustible obstructed and unobstructed, and combustible unobstructed	225 (20.9)	15 (4.6)	130 (12.1)	15 (4.6)	100 (9.3)	12 (3.7)	100 (9.3)	12 (3.7)
Combustible obstructed	168 (15.6)	15 (4.6)	130 (12.1)	15 (4.6)	100 (9.3)	12 (3.7)	100 (9.3)	12 (3.7)

PART B. STANDARD SIDEWALL SPRAY SPRINKLERS

	Light Hazard		*Ordinary Hazard*	
	Combustible Finish	**Noncombustible or Limited-Combustible Finish**	**Combustible Finish**	**Noncombustible or Limited-Combustible Finish**
Maximum distance along the wall (S), ft (m)	14 (4.3)	14 (4.3)	10 (3.1)	10 (3.1)
Maximum room width (L), ft (m)	12 (3.7)	14 (4.3)	10 (3.1)	10 (3.1)
Maximum protection area ft^2 (m^2)	120 (11.2)	196 (18.2)	80 (7.4)	100 (9.3)

PART C. EXTENDED COVERAGE (EC) UPRIGHT AND PENDANT SPRAY SPRINKLERS

	Light Hazard		*Ordinary Hazard*		*Extra Hazard*		*High-Piled Storage*	
Construction Type	**Protection Area, ft^2 (m^2)**	**Spacing (max.), ft (m)**	**Protection Area, ft^2 (m^2)**	**Spacing (max.), ft (m)**	**Protection Area, ft^2 (m^2)**	**Spacing (max.), ft (m)**	**Protection Area, ft^2 (m^2)**	**Spacing (max.), ft (m)**
Unobstructed	400 (37.2) 324 (30.1) 256 (23.8)	20 (6.1) 18 (5.5) 16 (4.9)	400 (37.2) 324 (30.1) 256 (23.8) 196 (18.2) 144 (13.4)	20 (6.1) 18 (5.5) 16 (4.9) 14 (4.3) 12 (3.7)	196 (18.2) 144 (13.4)	14 (4.3) 12 (3.7)	196 (18.2) 144 (13.4)	14 (4.3) 12 (3.7)
Obstructed noncombustible (when specifically listed for such use)	400 (37.2) 324 (30.1) 256 (23.8)	20 (6.1) 18 (5.5) 16 (4.9)	400 (37.2) 324 (30.1) 256 (23.8) 196 (18.2) 144 (13.4)	20 (6.1) 18 (5.5) 16 (4.9) 14 (4.3) 12 (3.7)	196 (18.2) 144 (13.4)	14 (4.3) 12 (3.7)	196 (18.2) 144 (13.4)	14 (4.3) 12 (3.7)
Obstructed combustible	NA	NA	NA	NA	NA	NA	NA	NA

TABLE 25.9 (*Continued*)

PART D. EXTENDED COVERAGE (EC) SIDEWALL SPRINKLERS				
	Light Hazard		***Ordinary Hazard***	
Construction Type	**Protection Area, ft^2 (m^2)**	**Spacing ft (m)**	**Protection Area, ft^2 (m^2)**	**Spacing ft (m)**
Unobstructed, smooth, flat	400 (37.2)	28 (8.5)	400 (37.2)	24 (7.3)
PART E. LARGE-DROP SPRINKLERS				
Construction Type		**Protection Area, ft^2 (m^2)**		**Spacing, (L) ft (m)**
Noncombustible unobstructed		130 (12.1)		12 (3.7)
Noncombustible obstructed		130 (12.1)		12 (3.7)
Combustible unobstructed		130 (12.1)		12 (3.7)
Combustible obstructed		100 (9.3)		10 (3.1)
PART F. EARLY SUPPRESSION FAST-RESPONSE (ESFR) SPRINKLERS				
	ESFR Sprinkler Up to 30 ft (9.1 m) in Height		***ESFR Sprinkler Up to 40 ft (12.2 m) in Height***	
Construction Type	**Protection Area, ft^2 (m^2)**	**Spacing, ft (m)**	**Protection Area, ft^2 (m^2)**	**Spacing, ft (m)**
Noncombustible unobstructed	100 (9.3)	12 (3.7)	100 (9.3)	10 (3.1)
Noncombustible obstructed	100 (9.3)	12 (3.7)	100 (9.3)	10 (3.1)
Combustible unobstructed	100 (9.3)	12 (3.7)	100 (9.3)	10 (3.1)
Combustible obstructed	NA	NA	NA	NA
PART G. MAXIMUM ALLOWABLE DEFLECTOR DISTANCES BELOW THE CEILING FOR VARIOUS SPRINKLERS[a]				
Sprinkler Type	**Maximum Distance in. (mm)**			
SSU/SSP	12 (305)			
Standard sidewall	6 (152)			
EC upright and pendant	12 (305)			
EC sidewall	6 (152)			
Large drop	8 (203)			
ESFR	14 (356)			

Source: Adapted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, National Fire Protection Association®, Quincy, MA 02169.

[a]Greater distances are permitted based on construction type, special listings, or both.

Notes: SI units were added by the text authors (are not from original source).

Obstructed: depth, spacing, and openness of structural members impede heat flow to the sprinkler head and/or disrupt the spray pattern.

Unobstructed: structural members do not impede the operation of the sprinkler head.

TABLE 25.10 Maximum Floor Areas for Sprinkler Systems

The maximum floor area on any one floor to be protected by sprinklers supplied by any one sprinkler system riser (or combined system riser) is:

Hazard	Area, ft^2 (m^2)
Light Hazard	52,000 (4831)
Ordinary Hazard	52,000 (4831)
Extra Hazard (hydraulically calculated)	40,000 (3716)
High-Piled Storage	40,000 (3716)

Source: Based on the *Fire Protection Handbook*, 18th ed., © 1997, National Fire Protection Association, Quincy, MA 02269.

Notes: Floor area occupied by mezzanines shall not be included in the above areas. Where single systems protect extra hazard or high-piled storage and ordinary or light-hazard areas, the extra hazard or storage area coverage shall not exceed the floor area specified for that hazard and the total area coverage shall not exceed 52,000 ft^2 (4831 m^2).

the walls and high enough on the walls to prevent the fire from getting above the sprinklers. This water near the ceiling also tends to cool gases at the ceiling, reducing the likelihood of excessive sprinkler openings.

The added cost of residential sprinkler systems may be recovered in several ways. As with other buildings, reductions in fire insurance rates will be helpful, although in residences the payback time is rather long. Zoning could permit smaller parcels of land for sprinkler-protected residences, since separation between buildings is less important when sprinklers protect both buildings.

(f) Quick-Response Sprinklers

All light hazard occupancies are now required to have quick-response (also called *fast-response*) sprinklers. These include hotels, motels, offices, and other buildings where faster sprinkler operation could enhance life safety. One measure of thermal sensitivity is the response time index (RTI), which indicates how fast the sprinkler can absorb sufficient heat from its surroundings to cause activation. It is expressed as the square root of meters-seconds. Quick-response (fast-response) sprinklers have an RTI of 50 or less. Standard-response sprinklers have an RTI of 80 or more—usually substantially more. Conventional automatic sprinklers generally have an RTI of 250 to 300.

Because of the thermal lag inherent in the glass bulb (or fusible link), the sprinkler body, and the water within sprinkler pipes, air temperature around a sprinkler may reach 1000°F (538°C) before a standard sprinkler, rated at 175°F (79°C), actually opens. The fast-response sprinkler's operating element has a smaller mass, enabling it to respond to the air temperature rise more quickly.

(g) Early Suppression Fast-Response (ESFR) Sprinklers

See Table 25.9, part F. These sprinkler heads are tested for their ability to suppress specific high-challenge fire hazards encountered in high-piled storage. They operate at a higher pressure and flow, and the water droplets produced depend upon momentum rather than gravity to penetrate to the bottom of high-velocity fire plumes. These sprinkler heads require a minimum water pressure of 50 psi (345 kPa) and a minimum flow of 100 gpm (6.3 L/s). They have largely replaced large-drop sprinklers (Table 25.9, Part E) that depended on the weight of the water droplet to penetrate the fire plume.

(h) Extended Coverage Sprinklers

See Table 25.9, parts C and D. These are limited to a type of unobstructed construction consisting of flat, smooth ceilings of a slope not exceeding 2 in. per foot (158 mm/m). Note that a smooth ceiling means that luminaires and air grilles are flush or recessed, not suspended from the ceiling. Such sprinklers, however, can also be specifically listed for "noncombustible obstructed" construction, or as upright and pendant sprinklers within trusses or bar joists having web members not more than 1 in.

(25 mm) thick, or where specifically listed for flat, smooth ceilings of a slope not exceeding 4 in. per foot (316 mm/m).

(i) Future Developments

Quick-response, early suppression (QRES) sprinklers were proposed several years ago. This approach would use the same principles as an ESFR sprinkler, but with a smaller orifice suitable to lighter-hazard occupancies. The QRES approach never really materialized, replaced instead by control mode specific application (CMSA) sprinklers.

In future sprinkler systems, different types of sprays may be ejected from a single sprinkler head: one spray of larger droplets to penetrate the fire plume and thereby cool burning surfaces as well as adjacent surfaces, and another, finer spray to cool the ceiling itself.

(j) Wet-Pipe Systems

These are the most common and most simple systems, as shown in Fig. 25.18. They are filled with water under pressure and are limited to spaces in which the air temperature does not fall below 40°F (4.4°C). (Wet-pipe systems that contain antifreeze, and admit ordinary water when a sprinkler head opens, are included in this category; the type of antifreeze is limited when potable water supplies the sprinkler system.) In the wet-pipe system, sprinklers in the affected area are opened by heat-sensitive elements within the sprinkler heads themselves and immediately emit water.

A typical automatic wet-pipe sprinkler system is shown in Fig. 25.19. The building, a printing and publishing plant, is in the category of "Ordinary Hazard, Group 2" (see Table 25.8). The sprinkler design results in a nozzle spacing such that one

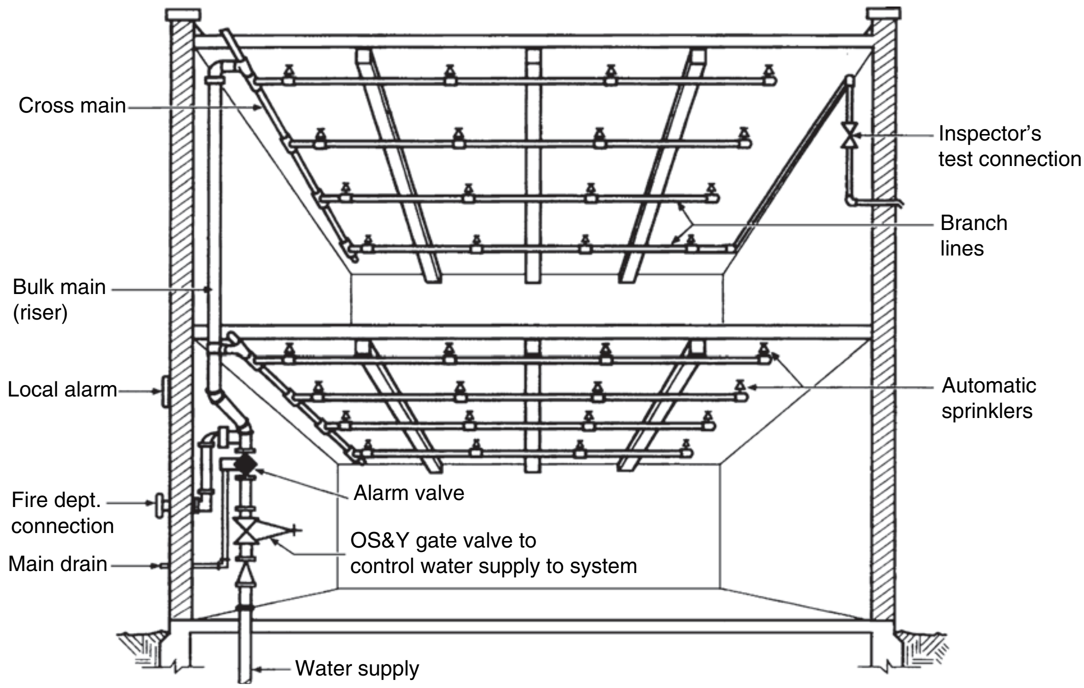


Fig. 25.18 *Wet-pipe sprinkler system. This most typical system is under water pressure at all times so that water will be discharged immediately when an automatic sprinkler opens. The automatic alarm valve shown causes a warning signal to sound when water flows through the sprinkler piping. OS&Y means "outside stem and yoke," describing a valve that clearly indicates the degree to which it is open or closed. (Reprinted with permission from the* Fire Protection Handbook*, 20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269.)*

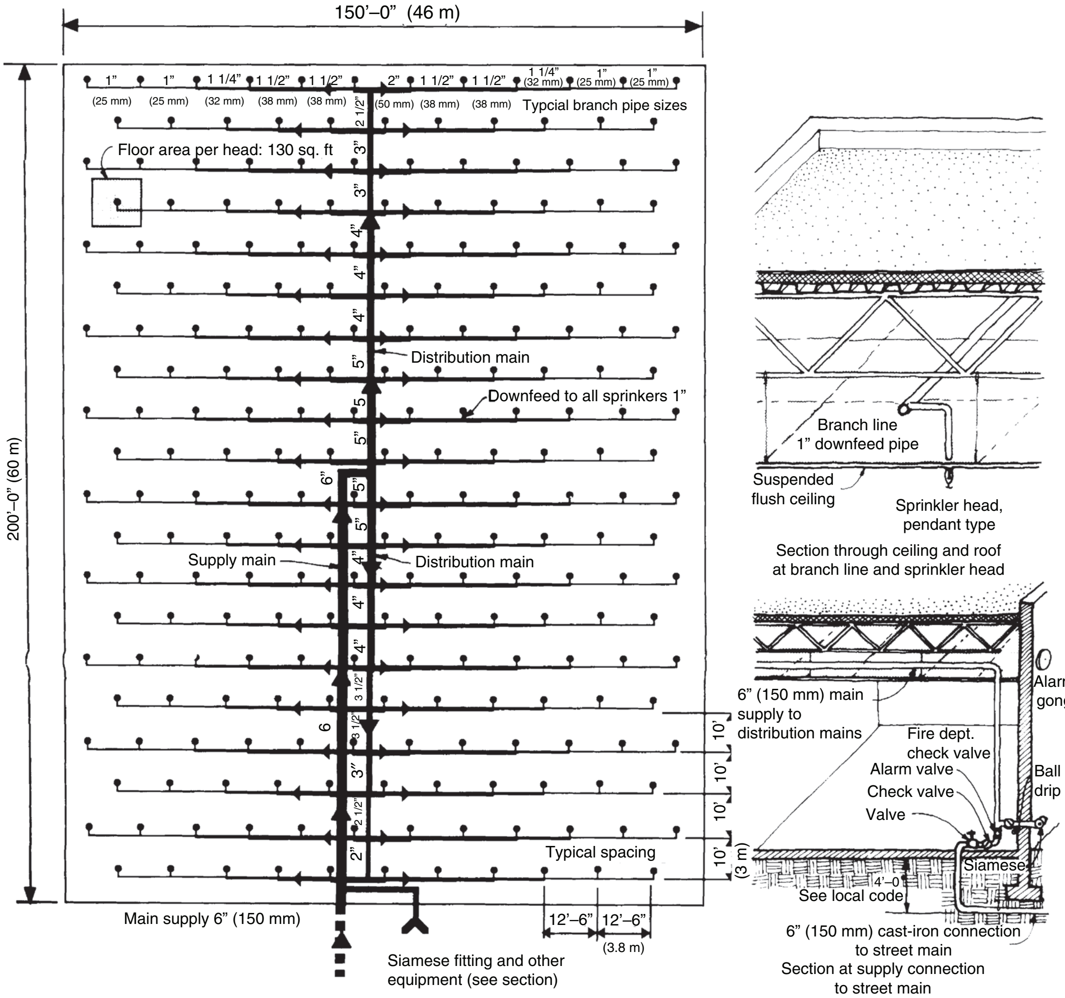


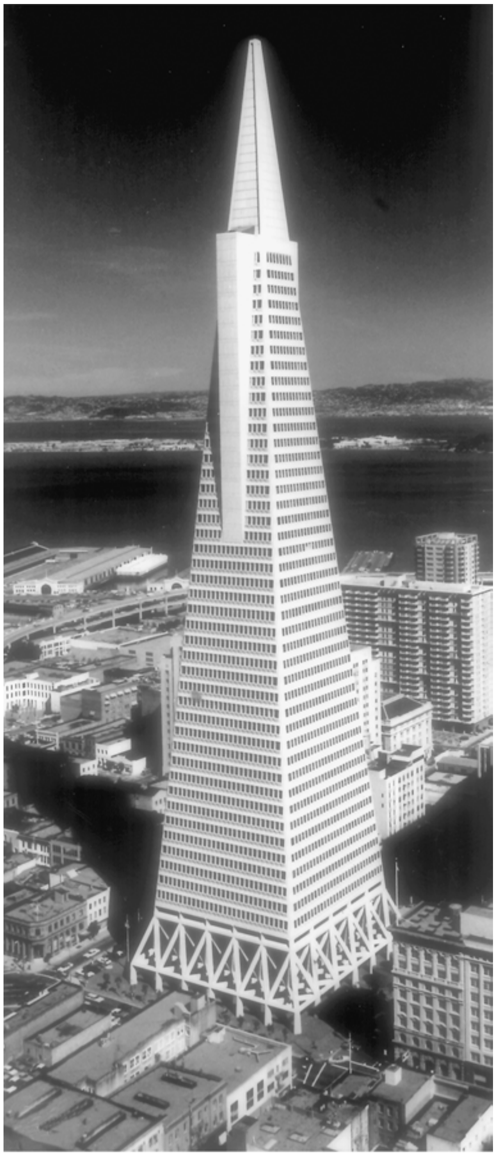
Fig. 25.19 *Plan of a sprinklered industrial building, ordinary hazard occupancy, whose 30,000-ft² (2790-m²) floor area is protected by 230 sprinkler heads (average 130 ft² [12 m²] per sprinkler head). Sprinklers are closer together than the maximum allowed. Sprinklers (and standpipes) may use water from street mains when pressure is adequate. Either system may use pneumatic or gravity tanks. When the latter are used to supply both systems, an independent sprinkler reserve occupies the bottom, and the fire standpipe supply occupies the top. An auxiliary fire engine feed connection by siamese should be provided in all cases. Auxiliary sources and standby pressurization may be required if street main adequacy is questionable.*

nozzle (sprinkler head) takes care of 130 ft^2 (12 m^2) of floor area.

The Transamerica Building (Fig. 25.20) in San Francisco is an urban high-rise building with a wet-pipe system. Two fire pumps can deliver 750 gpm at 275 psi (47.3 L/s at 1896 kPa) discharge pressure; they draw water from city mains at 50 psi (345 kPa) or from a 5000-gal (18,925-L) closed tank in the basement. These pumps feed into two 6-in. (15-mm) diameter "express" risers, one in each stair tower, that run the full height of this 48-story office building. The risers serve both the sprinkler system and fire department hose lines. In each of three 16-story zones, "local" 6-in. (150-mm) diameter risers branch off to feed a 2-in. (50-mm) looped main at each floor.

The sprinkler piping is carried above suspended ceilings; pendant sprinkler locations are coordinated with the modular grid that also locates partitions, air diffusers, and utility jacks. There are provisions for moving sprinkler heads as tenants change. At regular intervals, tees have been provided with one outlet stubbed and capped for future use. Typical office spaces are served by fully recessed, ½-in. orifice, 165°F (12.7-mm, 74°C) pendant sprinklers. Exposed pendant sprinklers are used in toilet rooms and service areas.

Although the typical sprinkler system is served by a single riser with a main line and branch lines, there are two variations that increase reliability by providing some redundancy in the supply lines. Figure 25.21*a* shows the gridded system, where each branch is served from either end, allowing each sprinkler head to receive water from either direction in the branch line. Figure 25.21*b* shows the loop system, where each branch line can receive water from either direction.



(*a*)

Fig. 25.20 *Transamerica Building, San Francisco, California; William Pereira & Associates, Los Angeles, California, architects. (a) The pyramid form provides rentable floor areas ranging from 22,000 to 3000 ft² (2044 to 279 m²). (b) Sixth-floor sprinkler plan showing two risers, a looped feed main, and branch lines. (Courtesy of the Copper Development Association.)*

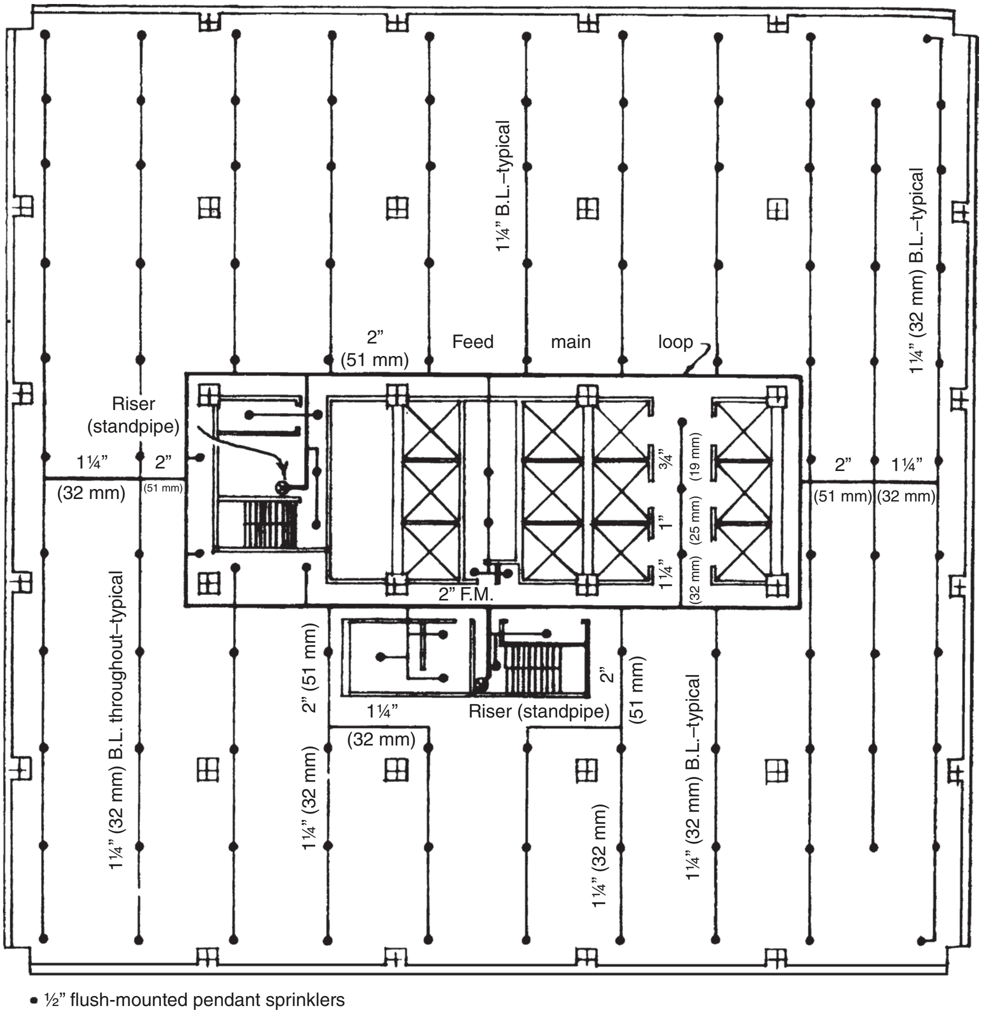
(k) Circulating Closed-Loop Systems

These wet-pipe systems use the rather large sprinkler piping to circulate water for water-source heat pumps. Water is not normally removed from this system, merely circulated. Water temperature in these systems must not exceed 120°F (49°C) or fall below 40°F (4°C). Such a system used for heating and cooling in a motel is shown in Fig. 25.22.

(l) Dry-Pipe Systems

As shown in Fig. 25.23, these systems are filled with compressed air (or nitrogen) rather than with water. They are used in unheated areas, including loading docks and cold-storage areas. As soon as a sprinkler head opens, the compressed air rushes out, allowing water to enter the formerly dry-pipe network through a *dry-pipe valve*. The system then functions like a wet-pipe system. The dry-pipe valve must be within a heated enclosure, since water under pressure is on one side of the valve. Also, due to the delay in delivering water throughout a previously dry piping system, a maximum system capacity of 750 gal (2839 L) is recommended.

Dry-pipe systems require a device to maintain design air pressure within the pipes. Air pressure might be maintained by a compressor, by an air receiver tank, or by connection to an existing pressurized air system (as in manufacturing operations). Dry-pipe systems also require a heated main control valve housing and the pitching of all piping to allow thorough drainage after use.



(*b*)

Fig. 25.20 *(continued)*

(m) Preaction Systems

In this system (Fig. 25.24), the pipes are filled with air that may or may not be under pressure. In addition to the sprinkler heads, either a heat- or a smoke-detection system is installed. The detectors are more sensitive than the sprinkler head. Water is held back by the *preaction valve*. When the heat or smoke detectors are activated, they open the preaction valve, an alarm is sounded, and water fills the pipes. The system then functions like a wet-pipe system, with water flow into a space occurring only upon the opening of a sprinkler head.

A variation on this system, known as a *combined dry pipe-preaction* (or *double-interlock preaction*) system, has pipes filled with compressed air. Heat or smoke detectors release the preaction valve and sound the alarm, but air pressure keeps water out of the piping until a sprinkler head opens.

Preaction systems are popular where the building's contents are especially subject to water damage—computer rooms, retail stores, museums, and so on—because the early alarm provided by water filling the piping often permits the fire to be found and extinguished manually, before any sprinklers open.

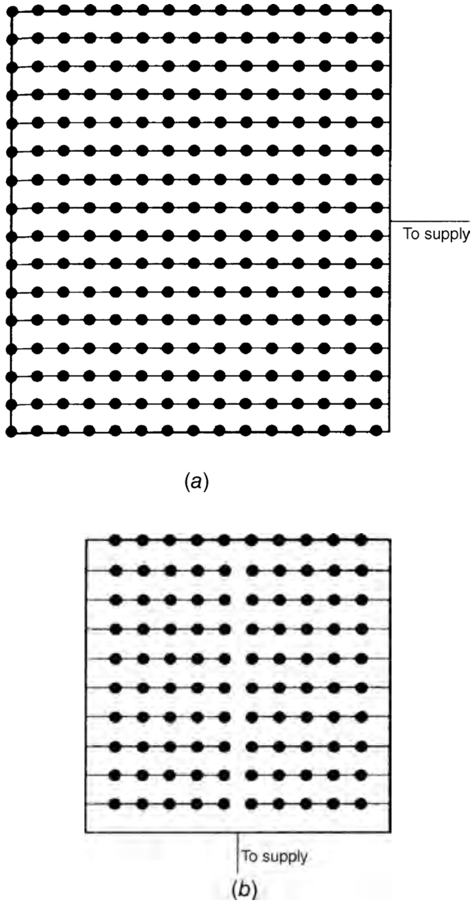


Fig. 25.21 *Alternative piping arrangements that provide more than one path for water. (a) Gridded systems supply water from either end of a branch line, offering the potential for water to come from either side of each sprinkler location. (b) Looped system, with the potential for each branch line to get water from either direction. (Reprinted from NFPA 13:* Standard for the Installation of Sprinkler Systems*; © 2012 National Fire Protection Association®. All rights reserved. This reprinted material is not the complete and official position of the National Fire Protection Association on the referenced subject, which is represented only by the standard in its entirety.)*

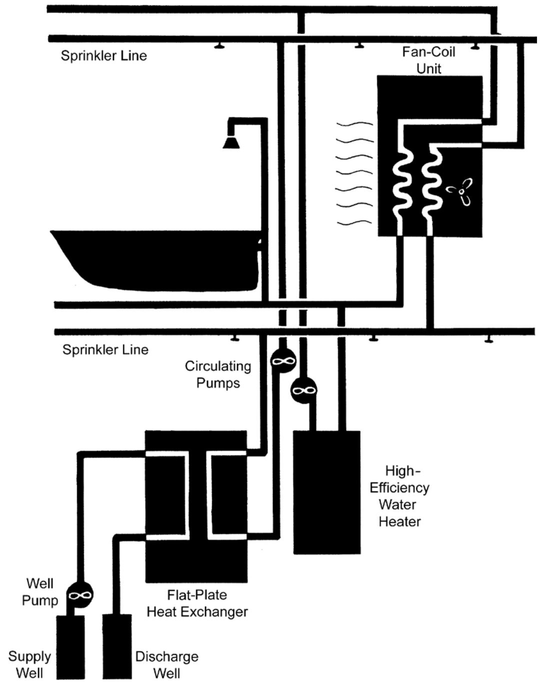


Fig. 25.22 *Circulating closed-loop sprinkler system, whose water is used by heating/cooling systems. This application is for a motel; a ground-source heat exchanger is supplemented by a water heater when required. (Courtesy of Montana Power. Redrawn by Amanda Clegg.)*

Designers must remember, however, that when the onset of the water discharge is delayed, a fire can quickly grow in size.

(n) Deluge Systems

These systems (Fig. 25.25) have *open* sprinkler heads on dry pipes. As with preaction systems, a separate heat- or smoke-detection system is installed. The detectors control a *deluge valve*, which, once opened, floods the system with water, and *all* heads emit water. Huge quantities of water are thus released. Deluge systems are used where extremely rapid fire spread is expected—in aircraft hangars, for example, or other places where flammable liquid fires may break out.

(o) Mist Systems

These are discussed last because they introduce the next section, fire-suppression alternatives to water. With a history of success in shipboard fires, they are being considered for wider application. NFPA 750 (NFPA, 2010) is the relevant standard.

A mist system offers fast initiation of an alarm as well as more rapid response to a fire. Smaller volumes of water mean less water damage, and the mist can move more easily around obstructions.

As an alternative to halon or other clean agent gases (Section 25.4), mist systems are more tolerant of small amounts of ventilation, reduce the radiant heat transfer from a fire, and eliminate the residues

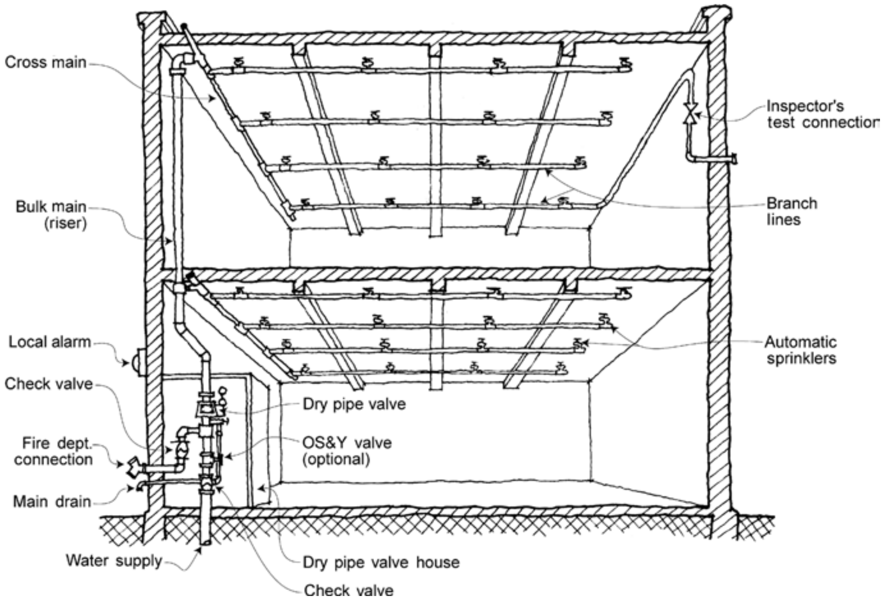


Fig. 25.23 *Dry-pipe sprinkler system for unheated occupancies. The system riser, cross mains, and branch lines are maintained at above-atmospheric air pressure. The dry-pipe valve and water supply must be within a heated enclosure. (Reprinted with permission from the* Fire Protection Handbook*, 20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269. Redrawn by Jonathan Meendering.)*

associated with many clean agent gases. They also eliminate the cost of refilling a system with expensive clean agent gases and allow a faster return to service after discharge.

These systems produce a much smaller water droplet, thanks to inlet pressures ranging from 45 to 4100 psi (310 to 28,270 kPa), depending upon the design of the sprinkler head. The heads are typically spaced closer together and have more sensitive thermal elements.

The NFPA *Fire Protection Handbook* (2008) suggests three classes of mist systems:

Class I mists have a droplet size ≤200 microns, the finest mists. This is achieved at the expense of flow rate and spray velocity, and requires significant input of energy to produce useful quantities. These mists are most suitable where enclosure reduces the need for spray momentum and fuel wetting is not critical (examples are liquid fuel fires and spray fires in enclosed spaces).

Class II mists have a droplet size from 200 to 400 microns. With larger drops, it is easier to achieve higher mass flow rates, and considerable surface wetting is possible. These mists are likely to be effective on fires involving ordinary combustibles.

Class III mists have a droplet size from 400 to 1000 microns. They can be generated by small-orifice sprinklers and fire hose fog nozzles, and deliver the highest mass flow rates.

The fire-extinguishing mechanisms of mists are shown in Fig. 25.26. Two primary mechanisms are heat extraction (through rapid evaporation of the finely divided water droplets) and oxygen displacement. Which mechanism dominates depends on whether the fire is poorly or well ventilated and the properties of the fuel. (Mist systems perform best in smaller enclosures with restricted ventilation, aided by heat entrapment and relatively easy oxygen displacement.) A third primary mechanism is the blocking of radiant heat. Secondary mechanisms in pool and spray fires are vapor/air dilution (mixing of water vapor and entrained air in the flammable vapor zone above the pool surface) and kinetic effects (the velocity of the flame front may be inhibited by small water droplets dispersed in a volume of flame).

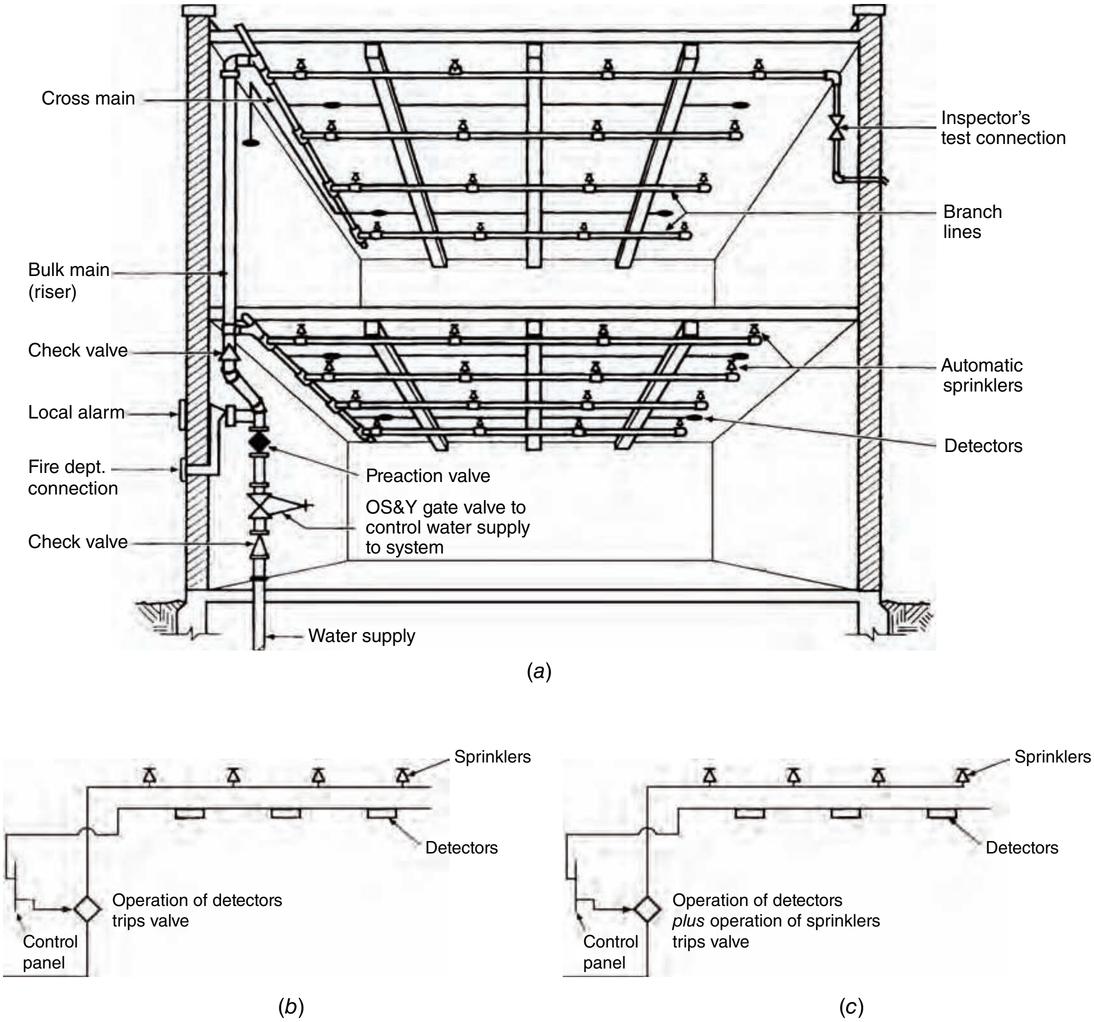


Fig. 25.24 *(a) Preaction sprinkler system. Sprinkler piping contains air until the preaction valve allows water to enter the system piping. (b) In a preaction system, detectors open the valve. (c) In a double-interlock preaction system, both the detectors and then a sprinkler must operate before the valve allows water to enter the system piping. (Reprinted with permission from the* Fire Protection Handbook, *20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269.)*

Tests in 1998 by the Institute for Research in Construction, National Research Council of Canada, demonstrated that cycling, rather than continuous, discharge from a mist system extinguished most test fires within a shorter time and ended all test fires with less water. A Class II spray with a twin-fluid (water and compressed air distributed separately, mixed at delivery) nozzle was used. The cycling discharges were "long water off" (50 seconds on, 30 seconds off) and "short water off" (30 seconds on, 20 seconds off). Compared to continuous discharge, cycling discharge produced higher room air temperatures near the ceiling and more rapid oxygen depletion. Both are threats to the contents and the occupants, yet both also make the mist system more efficient at extinguishing the fire. This resulted in less water used and, in most cases, a shorter fire-extinction period.

25.4 OTHER FIRE-MITIGATING METHODS

When water damage poses almost as much of a threat to a structure or its contents as does fire, a

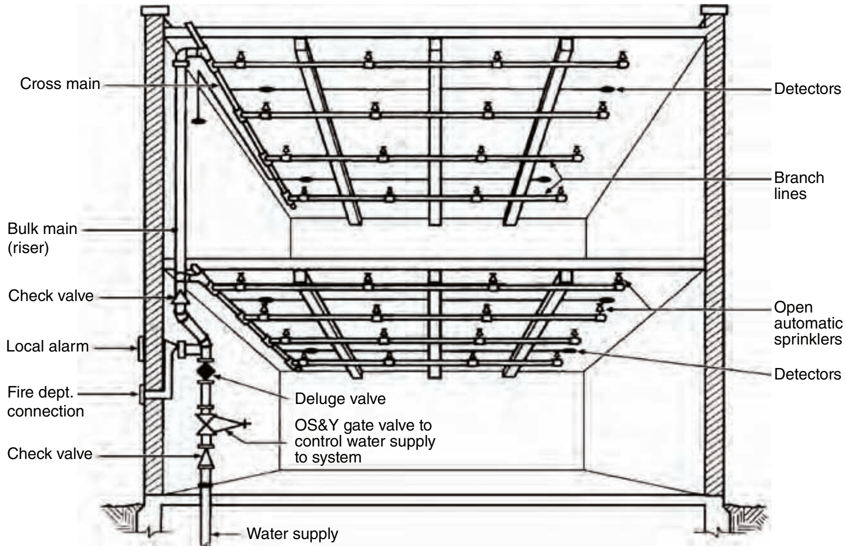


Fig. 25.25 *Deluge system. All sprinklers are open; therefore, all operate when water is allowed to flow into the system piping. (Reprinted with permission from the* Fire Protection Handbook*, 20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269.)*

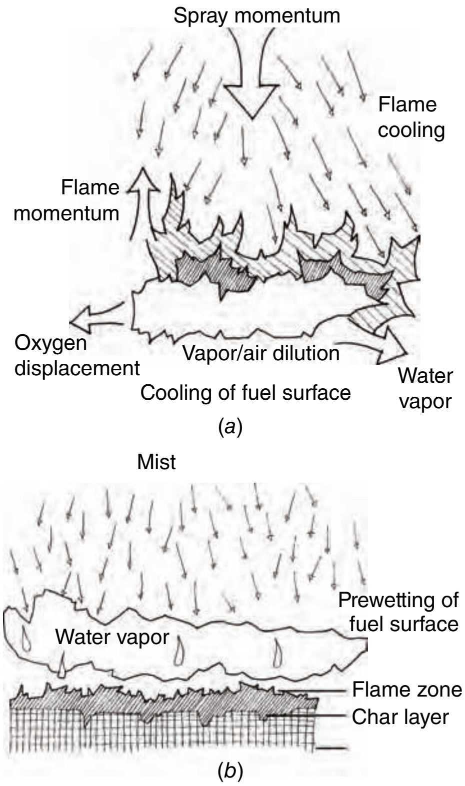


Fig. 25.26 *Water mist fire-extinguishing mechanisms.*
(a) Interaction of mist with fire in a pool of flammable liquid.
(b) Mist and flame interaction on a solid fuel with charring.
(Reprinted with permission from the Fire Protection Handbook*, 20th ed.; © 2008, National Fire Protection Association®. Quincy, MA 02269. Redrawn by Amanda Clegg.)*

variety of other fire-mitigating methods are available. The most passive of such measures are *intumescent* materials, which expand rapidly as they are touched by fire. This process creates air pockets that insulate a surface from the fire or swell a material until it blocks openings through which fire (or smoke) could have passed. Intumescent paints, caulks, and putties are available. Some intumescent materials come in ¼-in. (6.35-mm)-thick sheets, with various facing materials.

(a) The Rise and Fall of Halon 1301

Halogenated hydrocarbons, known commonly as *halons*, are gases (stored as liquids) in which one or more hydrogen atoms have been replaced by halogen atoms. Although the original hydrocarbons are often highly flammable gases, the substitution of halogen not only makes the gas itself nonflammable, but also gives it a flame-extinguishing capability by interrupting the chemical chain reaction in a fire.

Until the mid-1990s, the most widely used of these compounds was *Halon 1301*; the name signifies that its molecule contains one carbon atom, three fluorine atoms, no chlorine atoms, and one bromine atom. (When a fifth number is listed for halons, it refers to the number of iodine atoms. Hydrogen atoms are not accounted for.)

The advantages of Halon 1301 (and other halons) are that it can be released with relative safety through a flooding system into areas such as computer server rooms, quickly extinguishing a fire with little harm to the contents, no oxygen displacement to threaten life support, little demonstrated harm to people, and no residue left on electronic components. It is also lightweight and space-saving relative to other fire suppressants, as seen in the following subsections. Until the late twentieth century, Halon 1301 was used on all commercial aircraft and in many special building applications, such as computer rooms, museums and libraries, telephone exchanges, and kitchens.

Halon 1301, however, was subsequently identified as a long-lived, significant threat to the Earth's protective stratospheric ozone layer. Its production was thus phased out as of 1994. The search for replacements for Halon 1301 (and 1211) has led to mists (discussed previously), foams, inerting gases, and clean agents (discussed later), as well as special-application approaches beyond the scope of this book.

Inerting gas and clean agent replacements for Halon 1301, unlike water, actually protect the building's *contents* rather than its *structure*. They leave no sticky residue, such as most dry chemicals produce, and are therefore a popular choice where a clean fire-suppressing agent is required, people are present, and there are objects or processes of high value. Occasionally, they are used where water availability is low or where space cannot be found for systems that use other, bulkier fire suppressants.

(b) Foams

Because foams (masses of gas-filled bubbles) are lighter than water and flammable liquids, they float on the surface of a burning liquid, smothering and cooling the fire and sealing in vapors. Foams can be designed to inundate a surface or to fill cavities; they can be thin and rapidly spread or thick, tough, and heat-resistant. Some foams can be spread by foam-water sprinkler systems. Many foaming agents suited for various purposes are available. The NFPA *Fire Protection Handbook* presents a concise summary of foam extinguishing agents and systems.

Foams are defined by their expansion ratio (final foam volume to original foam solution volume before air is added). *Low-expansion foam* has an expansion ratio up to 20:1 and is used principally to extinguish burning flammable or combustible liquid spill or tank fires. *Medium-expansion foam* has an expansion ratio from 20:1 to 200:1; *high-expansion foam* has an expansion ratio from 200:1 to 1000:1. These last two types are used for indoor fires in confined spaces, to fill enclosures such as basement areas or holds of ships. They are also (at about 500:1) used to control liquefied natural gas (LNG)–spill fires and to help disperse the resulting vapor cloud.

Because foam breaks down and vaporizes its water content under attack by heat and flame, it must be applied at a sufficient volume and rate to compensate for water loss, leaving enough to produce a residual foam layer. Foam may easily be broken down by a water hose stream; turbulent air or rising combustion gases may divert foam from the burning area, especially if foam distribution occurs directly above a fire. Foam solutions are conductive, and therefore are not recommended for use on electrical fires. Firefighter entry to a foam-filled passage requires self-contained breathing apparatus and a life line (vision and hearing are reduced).

An example of high-expansion foam is shown in Fig. 25.27, the former North Central Airlines Hangar Building at the Metropolitan Airport in Detroit (Albert Kahn Associated Architects & Engineers, Inc.). The foam-generating equipment in this installation was designed to fill the 38,400-ft^2 (3567-m^2) hangar with 1,400,000 ft^3 (39,644 m^3) of foam to a height of 36 ft (10.8 m) in less than 12 minutes. Automatic devices, upon sensing an abnormal temperature increase, operate the foam generators, open roof vents, start smoke control exhaust fans in the vents, and transmit a fire alarm signal to the Airport Fire Department. Foam discharge is delayed 30 seconds while evacuation sirens sound to permit occupants to leave the fire area. Manual "override" controls allow personnel to start the system in the event of failure of the automatic controls, or to stop it if the fire is small and controllable by other methods.

The high-expansion foam is created by wetting a nylon net with a mixture of water and a special detergent soap concentrate. A large blower directs an air current through the net, producing an avalanche of foam. Suds blanket the fire, attacking it in several ways. The water in the suds converts to steam, absorbing the heat of the fire. The expansion of the foam into steam reduces the oxygen content to about 7%, which is insufficient to support active

Fig. 25.27 *Detergent foam (high-density) discharged from four units (two of which are seen in the illustration) after 3 minutes of operation. This installation at a hangar building at Detroit Metropolitan Airport smothers fire, prevents its spread, and will not harm airplanes or machinery. The system can handle combustible liquid fires. (Note also the supplementary grid of upright sprinklers directly below the roof surface.)*

combustion. A cooling effect is achieved by the wetting action of the breaking bubbles. The movement of air currents toward the fire to replace the rising hot gases draws the foam, supplied from the sides (rather than directly over the fire), to the center of the fire. There it blocks the airflow and cuts off the supply of oxygen. The fire, thus contained and diminished, can be approached by firefighters for further control.

Aircraft are not harmed by the foam. Delicate machinery that might be injured by high-velocity streams of water is undamaged and left clean when the foam is rinsed away. The structure—in this case, an open steel frame with a metal roof deck—is protected from high temperatures that might weaken it and cause it to collapse.

(c) Carbon Dioxide (CO_2)

Among other inerting gases, CO_2 has long been used to prevent ignition of potentially flammable mixtures and extinguish fires involving flammable liquids or gases. Although inerting gases certainly help to extinguish fire by displacing oxygen, they are even more effective by acting as a heat sink, absorbing combustion energy and reducing the temperature of the flame/vapor mixture below that necessary to sustain combustion.

Because of its oxygen displacement, CO_2 is often used in tightly confined spaces that are free of people or animals—for example, display cases, mechanical or electrical chases, and unventilated areas above suspended ceilings or below raised floors. It also finds applications in data centers, telecommunications equipment, and electrical equipment rooms—in short, wherever water damage is a major concern.

CO_2 is stored in cylinders as a liquid under great pressure, requiring roughly four times as many cylinders as would Halon 1301 for the same hazard. When it is released as a gas, it absorbs about 120 Btu/lb (280 kJ/kg) to provide cooling as well as smothering action. CO_2 is noncombustible and will not react with most substances. It does not conduct electricity and will not normally damage sensitive electronic equipment. There is no residual clean-up associated with its use as a fire-suppressing agent. It spreads upon discharge as a gas, but will stratify over time. When properly vented, the gas escapes to the atmosphere after a fire has been extinguished.

The main problem with CO_2 is that it must be used at concentrations of 21% to 62% of that of the air, depending on the fire's fuel. At a CO_2 concentration of 9%, however, loss of consciousness will occur after a few minutes. This may allow enough time for an awake occupant to escape, but it poses problems for firefighters or trapped persons. Another potential problem is that after the initial smothering and subsequent dissipation of the CO_2, smoldering embers might reignite.

A typical CO_2 automatic detection/suppression system (Fig. 25.28) has storage cylinders, a detection system, and a discharge valve that releases CO_2 into a piping system with discharge nozzles (rather similar to a sprinkler system).

(d) Clean Agent Gases

An array of replacement gases for Halon 1301 can be expected to meet demand for this type of fire suppressant. Initially, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are likely to be popular substitutes. One currently available alternative uses a potassium-based aerosol. Systems will typically resemble those used with CO_2 (Fig. 25.28). Confined and vital spaces such as

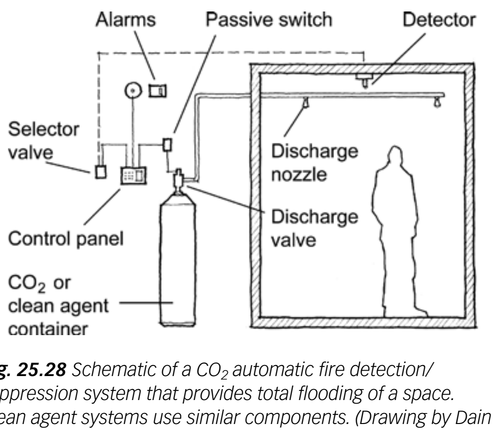


Fig. 25.28 *Schematic of a CO_2 automatic fire detection/suppression system that provides total flooding of a space. Clean agent systems use similar components. (Drawing by Dain Carlson; © 2004 Walter Grondzik; all rights reserved.)*

control rooms, computer and communication facilities, and emergency response centers are candidates for clean agent systems; consult the NFPA *Fire Protection Handbook* (2008) for system descriptions.

One replacement to gain approval is FM-200® (heptafluoropropane, CF_3-CHF-CF_3, ASHRAE designation HFC-227ea). It works in a manner similar to that of halons but with zero ozone-depletion potential. With a much shorter atmospheric lifetime than halons, it is also less threatening as a greenhouse gas contributing to global warming. It will typically require about 50% more cylinders than Halon 1301 for the same hazard.

FM-200 is a clean, nontoxic, odorless, electrically-non-conductive suppression agent consisting of carbon, fluorine, and hydrogen. It is stored in pressurized steel containers, and when released vaporizes and interrupts the combustion process by mixing with the air. Upon actuation it leaves no residue.

(e) Portable Fire Extinguishers

Most fires in buildings can be extinguished at an early stage with these commonly seen devices. Portable fire extinguishers are rated (or classified) based on the type of fire they are designed to fight. How many extinguishers are required and where they are located depend upon the hazard of the occupancy (as listed in Table 25.8). The following material is a short summary of NFPA 10: *Standard for Portable Fire Extinguishers* (2013).

Portable fire extinguishers are labeled as follows:

Class 1A to 40A. These extinguishers are used on "Class A" fires: involving ordinary combustibles such as wood, cloth, paper, rubber, and many plastics, and effectively suppressed by the heat-absorbing, cooling effects of water, the coating effects of dry chemicals, or the interruption of the combustion chain reaction provided by dry chemicals. The numerals refer to the relative extinguishing potential (a 40-capacity unit will extinguish 40 times as much as a 1). "A" refers to the contents: water, aqueous film-forming foam (AFFF), film-forming fluoroprotein foam (FFFP), and multipurpose dry chemical (ammonium-phosphate-base). (Halogenated agents are being phased out.)

Class 5B to 40B. These extinguishers are used on "Class B" fires: involving flammable or combustible liquids, flammable gases, greases, and similar materials that are best suppressed by excluding oxygen, by inhibiting the release of combustible vapors, or by interrupting the combustion chain reaction. The numerals refer to the approximate area (in square feet) of deep-layer liquid fire that an inexperienced operator can extinguish. "B" refers to the contents: smothering or flame-interrupting chemicals such as CO_2, dry chemicals, AFFF, or FFFP. (Halogenated agents are being phased out.)

Class C. "Class C" fires involve energized electrical equipment. The extinguisher contents are non-electrically-conducting, such as CO_2 or dry chemicals. (Halogenated agents are being phased out.)

Class A:B:C. Multipurpose dry chemical extinguishers filled primarily with ammonium phosphate and suitable for use with all three classes of fire. Unfortunately, ammonium phosphate has the disadvantage of leaving an especially hard residue unless promptly and thoroughly cleaned as soon as a fire is extinguished.

Class D. Class D fires involve combustible metals or metal alloys. The extinguisher contains dry powders, such as copper or graphite compounds or sodium chloride. These extinguishers are used on a variety of combustible metals; the specific combustible metal for which the extinguisher is intended is printed on the extinguisher's nameplate.

Class K. "Class K" fires involve cooking appliances that have vegetable oils and animal oils and fats—such as those found in commercial kitchens, restaurants, and cafeterias. These extinguishers contain a potassium acetate–based, low-PH agent that discharges as a fine mist to help prevent fires from grease splashes while the appliance cools.

A typical portable extinguisher is shown in Fig. 25.14*b*. A common Class A extinguisher contains 2½ gal (9.5 L) of water, weighs about 30 lb (13.6 kg), and emits a stream that can travel 30 to 40 ft (9 to 12 m). Fire extinguishers are rarely considered aesthetically pleasing, yet they need to be located in conspicuous places along regular paths of egress (Fig. 25.29). The requirements for maximum floor area served and maximum path to an extinguisher are shown in Table 25.11.

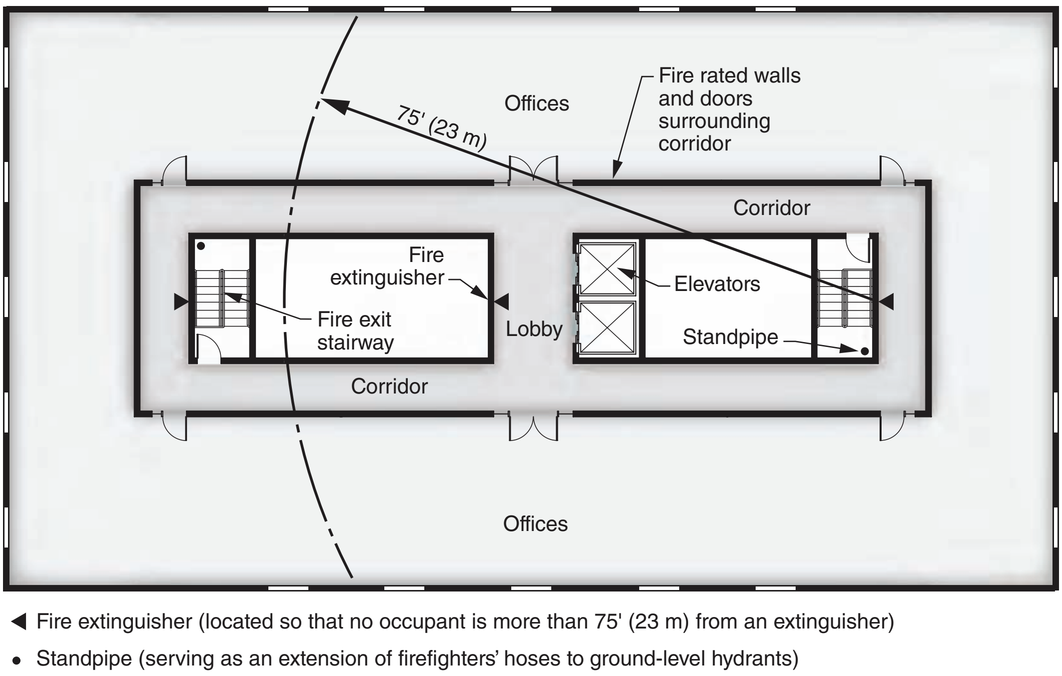


Fig. 25.29 *Location of portable fire extinguishers for a typical multistory office building. Extinguishers should be easily reached and placed in conspicuous locations along normal paths of protected egress, away from potential fire hazards. Note that three locations are shown.*

TABLE 25.11 Class A Fire Extinguishers

PART A. SIZE AND PLACEMENT FOR CLASS A HAZARDS			
	Occupancy		
	Light Hazard	**Ordinary Hazard**	**Extra Hazard**
Minimum rated single extinguisher	2-A[a]	2-A	4-A[b]
Maximum floor area per unit of A, ft^2 (m^2)	3000 (279)	1500 (139)	1000 (93)
Maximum floor area for extinguisher, ft^2 (m^2)	11,250 (1045)[c]	11,250 (1045)[c]	11,250 (1045)[c]
Maximum travel distance to extinguisher, ft (m)	75 (22.8)	75 (22.8)	75 (22.8)

PART B. MAXIMUM AREA TO BE PROTECTED PER EXTINGUISHER, ft^2 (m^2)			
	Occupancy		
Class A Rating on Extinguisher	**Light Hazard**	**Ordinary Hazard**	**Extra Hazard**
1A	—	—	—
2A	6000 (557)	3000 (279)	—
3A	9000 (836)	4500 (418)	—
4A	11,250 (1045)	6000 (557)	4000 (372)
6A	11,250 (1045)	9000 (836)	6000 (557)
10A	11,250 (1045)	11,250 (1045)	10,000 (929)
20A and more	11,250 (1045)	11,250 (1045)	11,250 (1045)

Source: Reprinted with permission from the *Fire Protection Handbook*, 20th ed., © 2008, National Fire Protection Association®, Quincy, MA 02169.

[a]Up to two water-type extinguishers each with 1-A rating can be used to fulfill the requirements of one 2-A rated extinguisher for light hazard occupancies.

[b]Two 2½-gal (9.5-L) water-type extinguishers can be used to fulfill the requirements of one 4-A rated extinguisher.

[c]This is the maximum area of a square that can be inscribed in a circle of 75-ft (22.8-m) radius where 75 ft (22.8 m) is the maximum distance to a fire extinguisher.

Note: SI units were added by the text authors (they are not from the original source).

25.5 LIGHTNING PROTECTION

Lightning is nature's most destructive force: The average lightning discharge is estimated at 200 million V, 30,000 A, and courses through a grounded object in less than a thousandth of a second. "Cold" lightning bolts have ample current, voltage, and duration to shatter and kill, but not to ignite combustibles. "Hot" bolts will ignite combustibles as well. Lightning protection can protect not just a building itself, but also serve to protect a building's electrical distribution system.

The decision on whether to protect a structure against lightning depends upon an evaluation of these factors:

1. Frequency and severity of thunderstorms.
2. Value and nature of building and contents.
3. Hazard to building occupants.
4. Building exposure; buildings in open and exposed areas are more susceptible to lightning than urban buildings, although very tall urban towers remain vulnerable.
5. Indirect effects. For example, loss of a water tower will seriously affect fire prevention and other services.

If a decision is reached to protect a building, it should be done completely and properly, with Underwriters Laboratories (UL) label equipment (Label A and B) and UL-approved installation (Label C). A partially protected building is in reality an improperly protected building, which might be worse than one with no protection at all.

The relevant standards are NFPA 780: *Standard for the Installation of Lightning Protection Systems* (NFPA, 2014), and UL Standard 96A, *Standard for Installation Requirements for Lightning Protection Systems* (UL, 2007). The subject of lightning protection is complex, and the design of an adequate system is best left to specialists. Design considerations and available materials are discussed briefly in the following material.

There is no known method of protection that will prevent the occurrence of a lightning stroke. The basic principle in lightning protection is, therefore, to provide a continuous metallic path to solid (low-resistance) ground for a lightning stroke. This approach will prevent the stroke from passing through the nonconductive portions of a building, accompanied by intense heat and very large mechanical forces that result from the high resistance of such a path.

Any lightning protection system includes one (usually more) *air terminals* (pointed copper or aluminum rods projecting above a structure); *ground terminals* embedded in highly conductive soil (or via a network of buried wires if the soil is nonconductive, such as bedrock or very dry soil); and *down conductors* that connect air and ground terminals. The conductors may be exposed on the building's exterior or concealed within a structure.

Three techniques for protecting structures from lightning are shown in Fig. 25.30. All three offer the lightning stroke a good conductor above the level of the protected nonconductive structure. The lightning stroke is drawn to the conductor, then conducted harmlessly to the earth. (Trees can be similarly protected.)

(a) Franklin Cone

A *Franklin cone* (Fig. 25.30*a*), named for Ben Franklin, is simply a mast with a conductor running straight to ground. A "cone of protection" is formed that protects the objects within it from strikes by absorbing the lightning stroke at the mast and grounding it harmlessly. The closer an object to the ground and the mast, the better the protection: Buildings within an interior solid angle of 60° get excellent protection, those within an angle of 90° get good protection, and those within an angle of up to 126° get fair protection. (A more complex "geometric" version is described in the NFPA *Fire Protection Handbook*.)

(b) Overhead Ground Shield Wire

Forming a continuous air terminal, this shield (Fig. 25.30*b*) is linear and horizontal, so the protected volume is a triangular prism, rather than a cone. This is most commonly used to protect overhead transmission lines.

It is recommended that both the single mast and the overhead ground shield project above any structure within the protected zone by at least 6 ft (1.8 m), and more height is better.

(c) Faraday Cage

Named for Michael Faraday, this approach (Fig. 25.30*c*) depends upon an open interconnected mesh covering a large, nonconducting mass (a building) to draw a lightning stroke and conduct it to earth. This leaves large areas of the roof exposed, so the higher the air terminals and the denser the mesh, the better the protection. An office tower, with high air terminals at close intervals, is shown in Fig. 25.31. Because this is the most common method used to protect buildings, some details follow.

All metallic objects on the roof should be bonded to a looped conductor that joins the air terminals. These air terminals commonly are placed

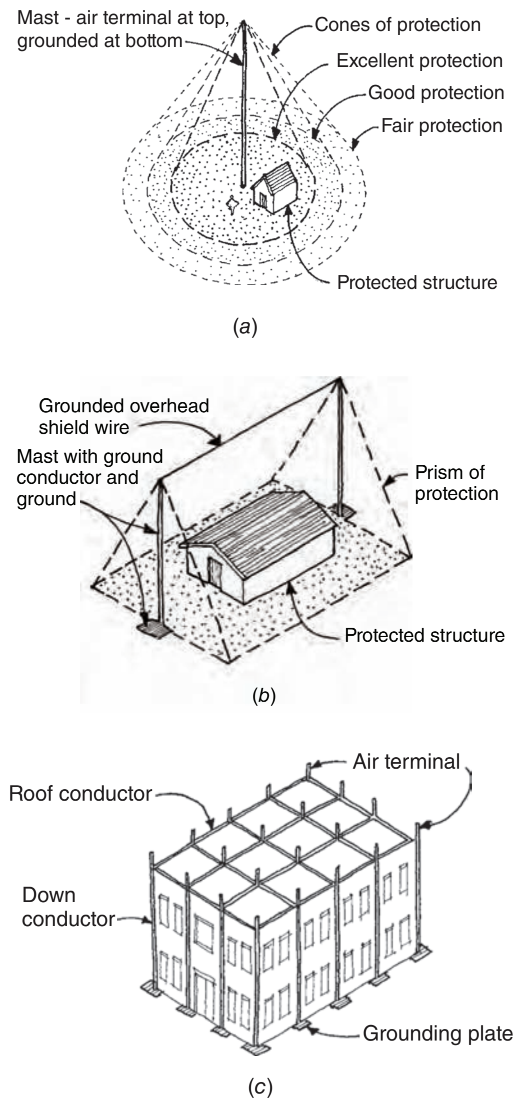


Fig. 25.30 *Three approaches to lightning protection. (a) The Franklin cone is provided by a central mast that acts as an air terminal, conductor, and ground. (b) The overhead ground shield wire provides a triangular prism protection zone. (c) The Faraday cage wraps a protective mesh around a structure.*

Fig. 25.31 *Lightning rods (air terminals) enliven the silhouette of the Bank of America Corporate Center in Charlotte, North Carolina. (Photo by Dale Brentrup.)*

both at roof edges and ridges at intervals of about 20 ft (6 m). The conductors usually are made of copper and are best housed in a plastic pipe conduit. Ground conductors, often called *counterpoise* conductors, are also installed to connect the earth terminals.

Metal roof and siding must not be substituted for air terminals and down conductors, unless constructed of 3⁄16-in. (4.8-mm) minimum sheet metal that has been made electrically continuous by bonding or an approved interlocking contact.

In *reinforced-concrete buildings*, concrete column steel reinforcing can be used for lightning conduction *if* the reinforcing steel is welded rather than merely tied. Where tied, and in buildings constructed with precast concrete panels, reinforcing steel (and other metal) within a few feet of lightning conductors should be bonded to the conductors to avoid arcing. Such arcing, as noted previously, is accompanied by heat and mechanical forces that can produce major structural damage and fire. Precast concrete buildings present a challenge because the reinforcing steel within precast panels is not typically interconnected.

In *steel structure buildings*, the columns relatively easily become lightning conductors. Care must be taken to adequately bond both the tops and foundations of such columns to the air and ground terminals, respectively (Fig. 25.32).

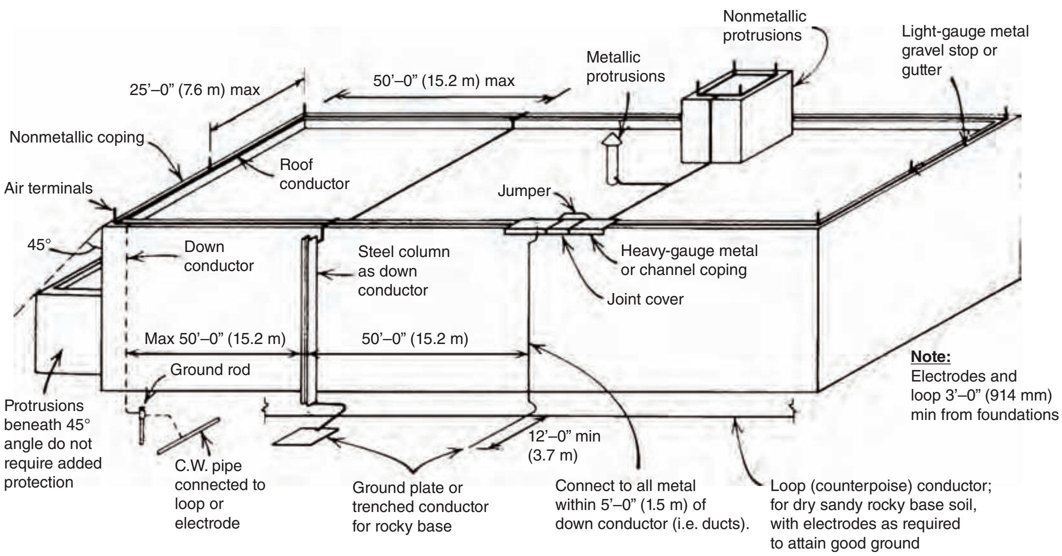


Fig. 25.32 *Diagram of a typical lightning protection system.*

(d) Lightning Arresters

A lightning arrester is a special type of *surge arrester* generally connected at one end to an overhead electrical line and at the other end to the ground. It thus suppresses any lightning voltage surges that appear in the electrical line so that equipment downstream on that line is not damaged. A lightning arrester operates only when it senses a voltage surge. At that point, it conducts the surge to the ground through its own low resistance and partially dissipates the energy of the surge in the body of the arrester. Once the surge has passed, the arrester returns to its high-impedance quiescent state, presenting an open-circuit connection to the normal voltage line to which it is connected.

(e) High-Rise Buildings

Lightning protection systems are particularly important for very tall buildings. Figure 25.33 shows the schematic diagram for the John Hancock

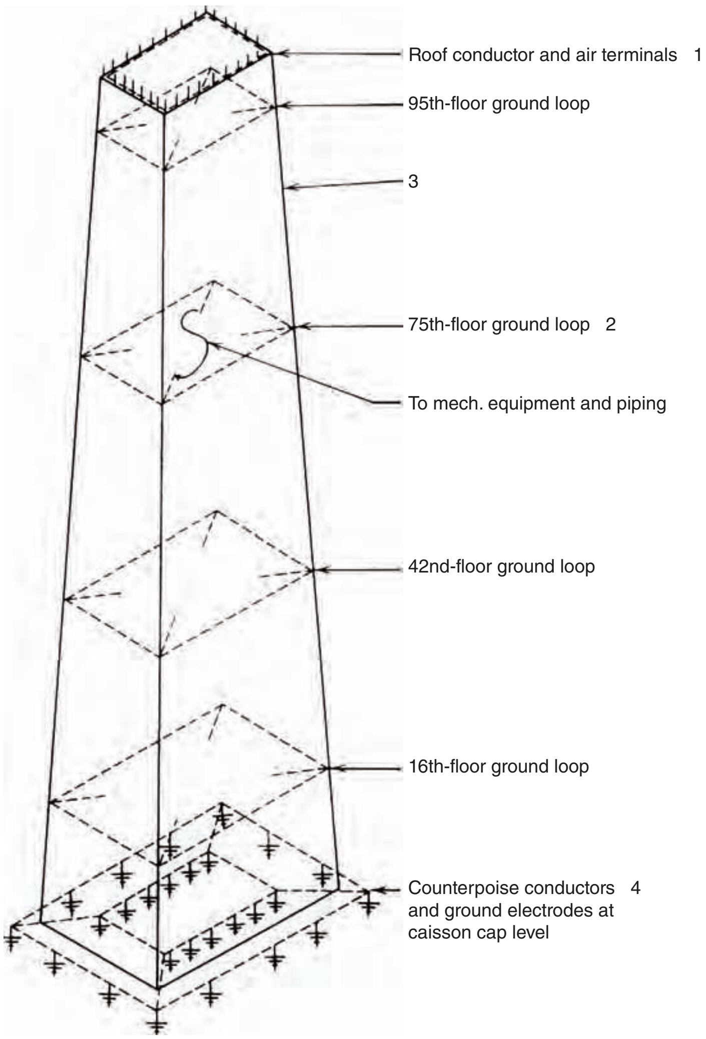


Fig. 25.33 *Lightning protection for the John Hancock Center, Chicago. Air terminals with roof conductors (1) are bonded to building steel and looped to ensure that a single wiring break will not fault the system. Intermediate-floor ground loops (2) with connections to building mechanical equipment and piping protect against side-effect flashover to people or equipment. Building structural steel (3), properly bonded together, is used as a down conductor. Counterpoise conductors (4) cross-connect ground electrodes with ground conductors located below the minimum groundwater level to ensure adequate and uniform dissipation of the charge. (Reprinted by permission from Jensen (ed.),* Fire Protection for the Design Professional*; © 1975 by Van Nostrand Reinhold Company, Inc.)*

Center in Chicago, a structural steel building of unusual height. Intermediate loops at the mechanical equipment floors help to overcome the problem posed by the poorer conductivity of metal piping systems, which can become relatively high-impedance paths for lightning, with resultant destructive effects. The intermediate loops are connected to each outside column, as well as to the main electrical, plumbing, air-conditioning, and fire protection risers. These loops are also connected to both the roof conductor and the ground counterpoise conductor.

FIRE ALARM SYSTEMS

25.6 GENERAL CONSIDERATIONS

A fire alarm system serves primarily to protect life and secondarily to prevent property loss. Because buildings vary in occupancy, flammability, type of construction, and value, a fire alarm system must be tailored to the needs of a specific facility. In schools, for instance, where the paramount consideration is rapid, orderly evacuation, the same general type of system will be used from project to project, although the means of automatic detection will vary with construction type, building height, specific area use, furnishings, and staffing. The fire alarm is part of the overall fire *protection* system of a building. In particular, it overlaps with the design of safe egress and smoke/fire control in matters such as fan control and smoke venting, smoke door closers, rolling shutters, elevator capture, and the like. These automatic functions are initiated by operation of the alarm system but are designed in accordance with the overall fire protection plan.

Like other alarm systems, a fire alarm system has three basic parts: signal initiation, signal processing, and alarm indication (see Fig. 25.34). The signal initiation can be manual (pull stations or telephones) or automatic (fire and smoke detectors and/or water flow switches). The alarm signal is processed by some sort of control equipment, which in turn activates audible and visible alarms and, in some cases, alerts a central fire station or municipal authorities.

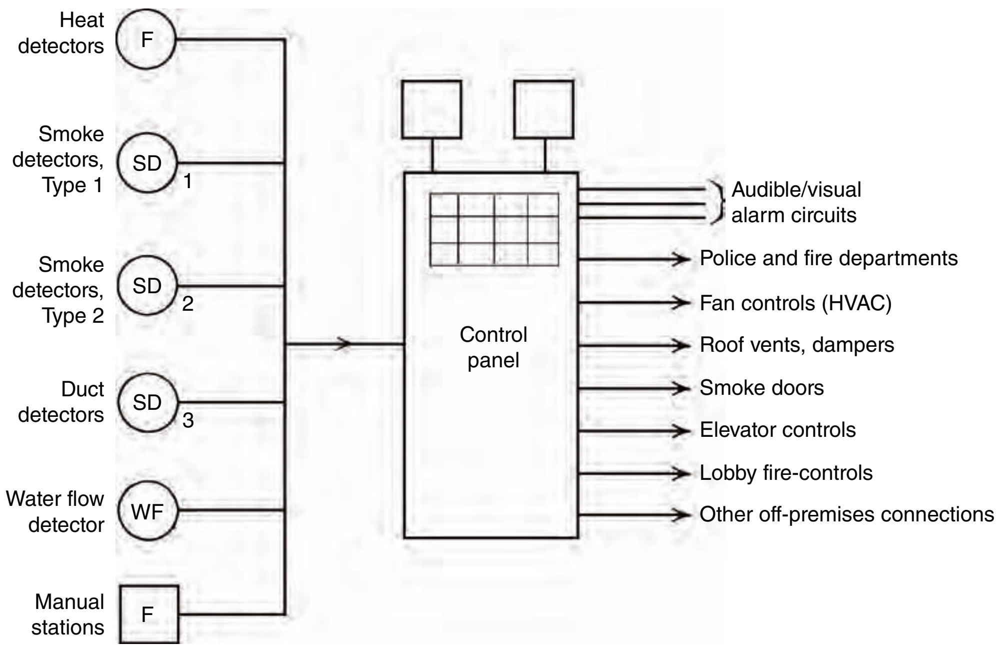


Fig. 25.34 *Typical simplified arrangement of a building fire alarm system. Multiple circuits, zoning, and other accessories such as annunciators are not shown. In a protected-premises (local alarm) system, the off-premises connections to police, fire department, and other central stations do not exist.*

25.7 FIRE CODES, AUTHORITIES, AND STANDARDS

NFPA codes (they are actually standards awaiting legislative adoption into codes) are published by the National Fire Protection Association (NFPA). They bear directly on fire alarm system arrangements. There are probably more codes and standards in the area of fire protection than in any other area, with the possible exception of structural design. Although the following documents are devoted primarily to fire protection and life safety, they also govern the type of fire alarm system to be installed, its components, and its installation.

NFPA 101: *Life Safety Code.* Specifies the means of egress, the type of fire alarm system, and the type and location of fire and smoke detection equipment for all types of occupancies.

NFPA 70: *National Electrical Code*. Particularly Article 760, *Fire Alarm Systems*.

NFPA 72: *National Fire Alarm and Signaling Code*.

NFPA 90A: *Standard for the Installation of Air-Conditioning and Ventilating Systems*.

NFPA 90B: *Standard for the Installation of Warm Air Heating and Air-Conditioning Systems*.

NFPA 92: *Standard for Smoke Control Systems in Malls, Atria, and Large Spaces*. This code provides a one-stop source for smoke control system design rules.

NFPA 99: *Health Care Facilities Code*.

NFPA 110: *Standard for Emergency and Standby Power Systems*.

NFPA 111: *Standard on Stored Electrical Energy Emergency and Standby Power Systems*.

ANSI (American National Standards Institute). This organization does not develop standards; it accredits standards that are prepared by professional and technical societies and associations. Approval and listing by ANSI validates an organization's standards development process.

ICC/ANSI 117.1: *Accessible and Usable Buildings and Facilities*. This standard specifies requirements to make buildings accessible to and usable by people with physical disabilities.

ICC (International Code Council). Publishes the *International Fire Code*, a unified code that has generally supplanted legacy regional codes in the United States.

HUD (Department of Housing and Urban Development). Publishes requirements for residential buildings and care-type facilities. FHA minimum property standards are included here.

UL (Underwriters Laboratories): Numerous performance standards are published by Underwriters Laboratories, Inc. UL laboratories test equipment for inherent safety and for performance according to the manufacturer's specification. A product is "listed" if the equipment passes UL safety and performance tests. Some UL standards related to fire protection include:

UL Detection Standards

38: Standard for Manual Signaling Boxes for Fire Alarm Systems

217: Standard for Single and Multiple Station Smoke Alarms

268: Smoke Detectors for Fire Alarm Systems

268A: Standard for Smoke Detectors for Duct Application

346: Standard for Waterflow Indicators for Fire Protective Signaling Systems

521: Standard for Heat Detectors for Fire Protective Signaling Systems

539: Standard for Single and Multiple Station Heat Alarms

985: Standard for Household Fire Warning System Units

1730: Standard for Smoke Detector Monitors and Accessories for Individual Living Units of Multifamily Residences and Hotel/Motel Rooms

UL Alarm Standards

228: Standard for Door Closers-Holders, With or Without Integral Smoke Detectors

464: Standard for Audible Signal Appliances

827: Standard for Central-Station Alarm Services

1480: Standard for Speakers for Fire Alarm, Emergency, and Commercial and Professional Use

1638: Standard for Visual Signaling Appliances—Private Mode Emergency and General Utility Signaling

1971: Standard for Signaling Devices for the Hearing Impaired

In addition, several insurance groups (e.g., Factory Mutual) issue standards that may apply to a specific facility—in addition to local codes, standards, and fire marshal regulations. As with other aspects of construction, the architect/designer must ascertain which regulations have jurisdiction before proceeding with the design. In addition, all codes and standards undergo a cyclical updating process with new versions appearing on a regular basis. The specific recommendations given in the following sections are representative of good practice. Actual design must be based upon and must meet the requirements of *current* NFPA standards plus all codes having jurisdiction in the particular locale of a project.

25.8 FIRE ALARM DEFINITIONS AND TERMS

The following short list can serve as a primer for terminology that a designer may encounter in fire alarm work.

Addressable analog (smoke) detector. Also called an *intelligent detector*. This addressable (see next definition) smoke detector continuously measures the concentration of smoke or other products of combustion in its test chamber. It continuously transmits an analog (voltage or current) signal to its (intelligent) control panel that is proportional to this measurement. It does not transmit an alarm signal (see Fig. 25.46).

Addressable detector. A smoke or fire detector that communicates an alarm condition along with an individual identification (address), thereby immediately establishing the alarm's location. It responds to polling (testing) when it senses its unique identification (address) signal, "replying" with a signal indicating OK, trouble, or alarm.

Air-sampling detector. A system consisting of aspiration equipment and piping that draws air from a protected area to the detector, where analysis of the sampled air occurs.

Alarm signal. An audible and/or visual signal indicating a fire emergency, generally requiring immediate building evacuation.

Alarm verification. A technique for reducing false alarms. Common procedures include a requirement for alarming for a specific minimum time and a repeat alarm after initial reset.

Automatic system. A system in which an alarm-initiating device operates automatically to transmit or sound an alarm signal.

Auxiliary fire alarm system. See Section 25.9(c).

Break-glass. A false-alarm deterrent installed in manual fire alarm stations; a glass rod is placed across the pull-lever that breaks easily when the lever is pulled.

Coded alarm signal. An alarm signal that indicates the location of the fire alarm station that operated, by the pattern (code) of the audible signal.

Coded system. One in which not fewer than three rounds of coded alarm signals are sounded, after which the system may either be silenced or set to sound a continuous alarm.

Control unit (fire alarm panel). The controls, microprocessors, relays, switches, and associated circuits necessary to (1) furnish power to a fire alarm system, (2) receive and process signals from alarm-initiating devices and transmit them to indicating devices and accessory equipment, and (3) electrically supervise the system's circuitry.

Drift compensation. Adjustment function that compensates for detector sensitivity changes due to aging and environmental conditions. The adjustment may be automatic at the detector or manual/automatic at the control panel. Also referred to as *automatic gain control* in beam-type smoke detectors.

Dual-coded system. See Section 25.12(d).

Intelligent control panel. A control center that receives analog signals from detectors and, based on predetermined conditions (usually programmed into software or a microprocessor), determines whether an alarm situation exists. Sensitivity control, polling, and remote diagnostic testing of connected detectors are other functions usually found in these panels.

Listed, listing. Inclusion of a device in a list published by a recognized testing organization, such as UL, indicating that the device meets the requirements of the referenced standard.

Local fire alarm systems. See Section 25.9.

Manual system. One in which the alarm-initiating device is operated by direct human action to transmit or sound an alarm signal.

Master-coded system. See Section 25.12(b).

Multiplex system. An arrangement whereby a single pair of wires can carry more than one message (signal) at a time in either or both directions.

Noncoded system. See Section 25.12(a).

Presignal system. See Section 25.12(f).

Private mode. An alarm system installed in a location that has personnel specifically trained to act on receipt of an alarm signal.

Proprietary fire alarm system. See Section 25.9(e).

Public mode. An alarm system that alerts all of the protected spaces and occupants audibly and/or visually.

Rate-of-rise detector. A temperature detector that alarms when the rate of temperature rise exceeds a specific design level, usually 15F°/minute (8.3C°/min).

Remote station fire alarm system. See Section 25.9(d).

Selective-coded system. See Section 25.12(e).

Station, fire alarm. A manually operated alarm-initiating device. It may be equipped to generate a continuous signal (noncoded station) or a series of coded pulses (coded station).

Supervised system. A system in which a break or ground in the wiring that prevents the transmission of an alarm signal actuates a trouble signal.

Trouble signal. A signal indicating trouble of any nature, such as a circuit break or ground, occurring in a device or circuitry associated with a fire alarm system.

Zone-coded system. See Section 25.12(c).

25.9 TYPES OF FIRE ALARM SYSTEMS

Fire alarm systems can be classified according to several different characteristics, including location, application, connections, coding, and the degree of automation of the detection system. The last factor is the one most often found in manufacturers' literature. To avoid confusion, the classification system found in the *National Fire Alarm and Signaling Code* (NFPA 72) is used herein. This code classifies fire alarm systems essentially by location and function:

- Household fire warning systems.
- Protected-premises systems (local alarm).
- Off-premises systems (connections between local alarms and off-premises equipment and systems). This category includes auxiliary, remote station, proprietary, central station, and municipal fire alarm systems.

(a) Household Fire Warning Systems

The term is self-explanatory. These systems are discussed at some length in Section 25.26.

(b) Protected-Premises Fire Alarm System

This arrangement (as per Fig. 25.34), as the name indicates, is intended to sound an alarm only in the protected premises. Action in response to an alarm must be taken locally, either manually or automatically. Thus, notification to the fire department is manual, although fire-suppression systems can be set into operation automatically. This arrangement is applicable to privately owned facilities. When a building is unoccupied, notification to the fire department can come only incidentally, perhaps from a passerby. Local systems and their components are discussed in detail in Section 25.11.

(c) Auxiliary Fire Alarm System

This is simply a local system equipped with a direct connection to a municipal fire alarm box (Fig. 25.35). The received alarm signal is identical to that resulting from a manual alarm at that city box. Since the fire department is aware of all city box connections, arriving firefighters would always check the protected premises. This type of system is usually applied to public buildings such as schools, government offices, museums, and the like.

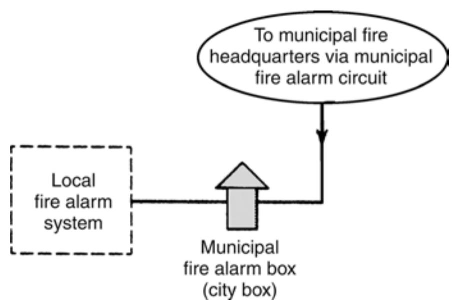


Fig. 25.35 *An auxiliary fire alarm system is hard-wired to the municipal fire department, generally via a city box. This type of connection is usually restricted to public buildings.*

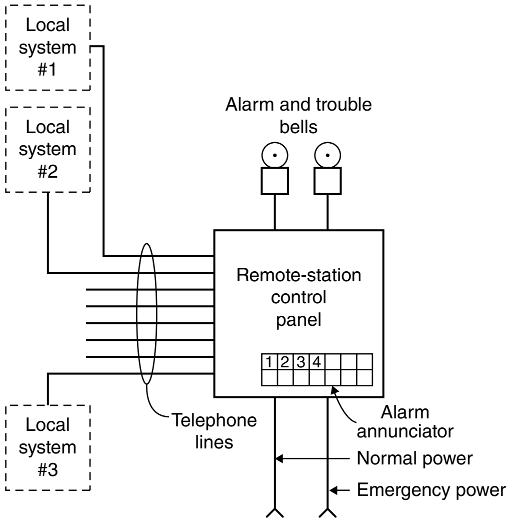


Fig. 25.36 *A remote station system transmits alarm, supervisory, and trouble signals to a remote location that is continuously attended. The required actions will be taken by those attending the remote stations.*

(d) Remote Station Protective Signaling System

This system (see Fig. 25.36) is similar to an auxiliary system, except that the alarm or trouble signal is transmitted via a leased telephone line to a remote location (a police station or a telephone-answering service) that is manned 24 hours a day. Notice of the alarm is then telephoned to the fire department. This arrangement is used in private buildings, such as stores and offices, which are unoccupied for considerable periods and for which reliance on a chance passerby to turn in a fire signal is unacceptable. An audible alarm circuit extended from a local system to a nearby building—as, for instance, from a store to a nearby residence—does *not* constitute a remote station system unless all the requirements of NFPA 72 are met.

(e) Proprietary Fire Alarm System

This system (see Fig. 25.37), which is applicable to large multibuilding facilities such as universities, manufacturing plants, and the like, utilizes a dedicated central supervisory station to receive signals from all buildings. In a proprietary system, this station is on the site and is manned by persons associated with the facility. A common arrangement is for the station to be located in a guardhouse or similar supervisory location, from which point alarms are sent manually to a fire department and/or on-site fire brigades. Other actions that must be taken on receipt of alarm or trouble signals are performed by facility personnel at the central supervisory location.

Information on the exact locale or zone within each building at which an alarm occurs is transmitted to the central supervisory location. The central station has an audible alarm, some sort of visual display that indicates the alarm location, and a printer that makes a permanent record of each alarm. As mentioned, these central supervisory

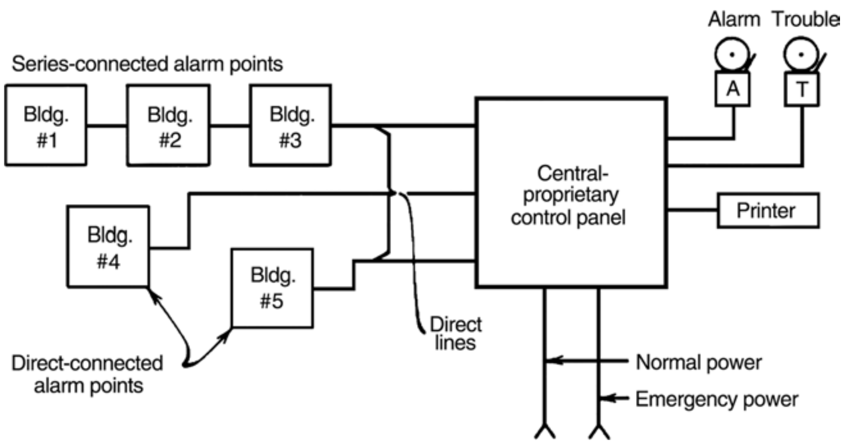


Fig. 25.37 *Block diagram of a proprietary fire alarm system. The entire system, including all local devices plus the central supervisory equipment, is the property of a single owner. The central supervisory installation is attended by facility personnel who are trained to respond appropriately to alarm, trouble, and supervisory signals.*

locations are frequently multipurpose, covering all aspects of facility security, plus, frequently, control functions such as energy management.

(f) Central Station Fire Alarm System

This arrangement is similar to that described for proprietary systems except that the system supervision and normally all of its equipment are owned and operated by a service company. In lieu of multiple buildings under one "ownership," a central station system supervises many individual unrelated local systems for a fee. Here too, operators of the central supervisory installation receive all signals from individual users and provide the required services, including alarm verification, fire reporting, and repairs when trouble signals are received. As with proprietary systems, central station consoles often supervise access control, intrusion alarms, and related systems.

25.10 CIRCUIT SUPERVISION

This common term refers to the circuit arrangements in fire alarm systems that indicate a malfunction in the wiring of alarm (and other) devices by sounding a trouble bell. The trouble signal is separate and distinct from an alarm signal. The extent of circuit supervision required varies with the type of facility and the specific code adopted by a jurisdiction. Minimally, an open circuit (break) or a ground in any part of the detector and manual station wiring will cause a trouble signal. In large, sophisticated systems, all of the wiring and circuitry is supervised, including the control panel(s), alarm device circuits, and even annunciator wiring.

In conventional systems (see Section 25.11), the supervision does not indicate where a fault lies, but only that a fault exists. It is up to the system operator to troubleshoot the system in order to locate the fault. Because this may be a protracted procedure, all codes require that the system wiring be such that a single break or a single nonsimultaneous ground will not prevent an alarm signal from being sounded beyond the break (Class B circuits) or on the entire circuit (Class A circuit).

25.11 CONVENTIONAL SYSTEMS

Manufacturers classify fire alarm systems by the type of information transmitted to the control panel by the detectors and the alarm devices. The simplest (and oldest) system is the conventional system (Fig. 25.38). A conventional system uses detectors and manual stations that transmit an alarm signal only. When they are in standby or quiescent state, they do not transmit. Such detectors and manual stations are called *conventional units*; hence, the same name is used for the entire system. The signals transmitted by all detectors, and by manual stations

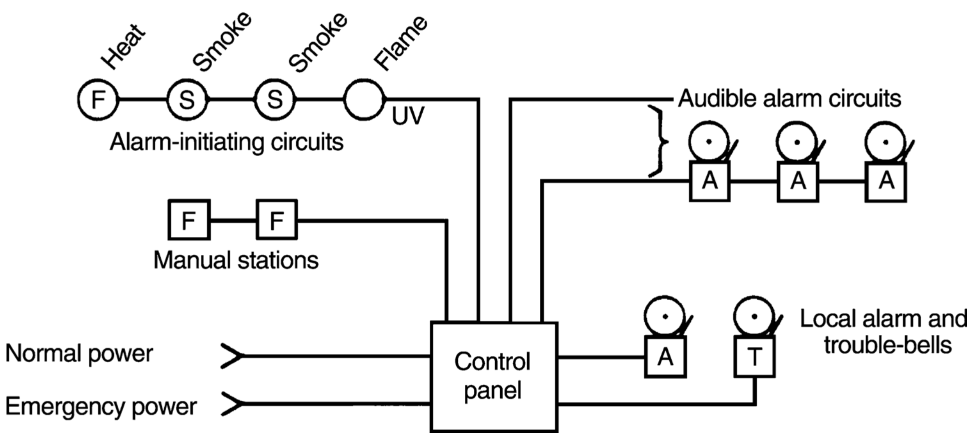


Fig. 25.38 *Simplified schematic diagram of a conventional fire alarm system. Alarm-initiating devices are connected together on detector circuits, as are manual stations and audible/visual alarm devices. The control panel receives identical signals from all detectors, manual stations, and alarm-initiating circuits.*

as well, are identical and therefore indistinguishable from each other.

In theory, the number of alarm-initiating devices (such as fire and smoke detectors) that can be wired to a single detector circuit is unlimited. (In practice, there are electrical limitations.) As a result, when an alarm signal is received from such a multiple-device circuit, there is no way of knowing which of the devices alarmed and whether the alarm represents an actual fire condition or a false alarm caused by dirt, moisture, a puff of smoke, a short circuit in the wiring, or a malfunction of a detector.

Smoke detectors of all types (ionization, photoelectric) are subject to false alarms activated by particulate matter in the air. Detectors are, by nature, threshold devices; raising sensitivity increases false alarms, and decreasing sensitivity shortens the crucial early-warning period. False alarms are not merely nuisances; in facilities such as hospitals, and in places of public assembly such as theaters, public office buildings, and mass eating facilities, a false fire alarm can result in serious business disruption, property loss, personal injury, and even death if panic ensues. As a result, conventional detectors in such buildings require continual maintenance and field sensitivity checks to minimize false alarms, which is an expensive and time-consuming procedure.

Because such facilities are so difficult and even dangerous to evacuate, most have fire and evacuation plans that call for some type of alarm verification before a general evacuation alarm is sounded. Because field experience has demonstrated that alarm verification can reduce false alarms appreciably without seriously degrading the early warning performance of combustion product detectors, recent editions of some fire codes now permit, or even require, alarm verification. This verification can be accomplished in conventional (hard-wired, zoned, nonaddressable) systems in a number of ways, including:

- Requiring activation of at least two cross-zoned detectors in a single area
- Requiring that a detector repeat its alarm after being reset (applicable only to systems with remote reset capabilities)
- Requiring that a smoke detector continue to alarm for a minimum period of time, thus eliminating smoke puffs as the cause of an alarm
- Physically inspecting the site protected by the detector to visually determine whether the alarm is actual or false

This last technique for alarm verification is probably the most foolproof, but it is also the most difficult because it requires knowledge of the exact location of the alarming detector. This is possible only if detectors are grouped into zones and each zone is annunciated individually (Fig. 25.39). To assist in localizing areas in a building by annunciation, zones are wired to contain as few devices as possible, the ultimate arrangement being a separate zone for each detector. As can be seen in Fig. 25.39, as the number of zones increases, so does the necessary wiring and, as a result, so do the installation costs. Thus, a balance must be struck between two requirements: the need for more zones to localize and thereby simplify alarm identification and verification, and limitation of the increased cost of zoning. The balance point depends upon the type of facility being protected. All modern conventional systems are solid-state, and all but the smallest use a wiring system called *multiplexing*.

Multiplexing uses a time-sharing electronic technique to transmit and receive multiple signals on a single two-wire communications circuit. This has the great advantage of reducing the primary cost item in large hard-wired systems—individually wired circuits. The alarm and audible signal devices in standard multiplexed systems are the same as those in conventional hard-wired systems. Only the system wiring and the panel arrangement change. Zones, and even coding, are substantially unaltered, although the reduction in wiring costs permits the use of smaller zones. Some multiplexed systems are hybrid, using multiplexed detector circuits and hard-wired audible/visual alarm circuits. An additional advantage of multiplex panels is that they can be reprogrammed readily, which is emphatically not the case with hard-wired relay panels.

25.12 SYSTEM CODING

(a) Noncoded Systems

Noncoded systems are *continuous* ringing evacuation arrangements using manual and automatic alarm initiation. If desired, the devices can be zoned

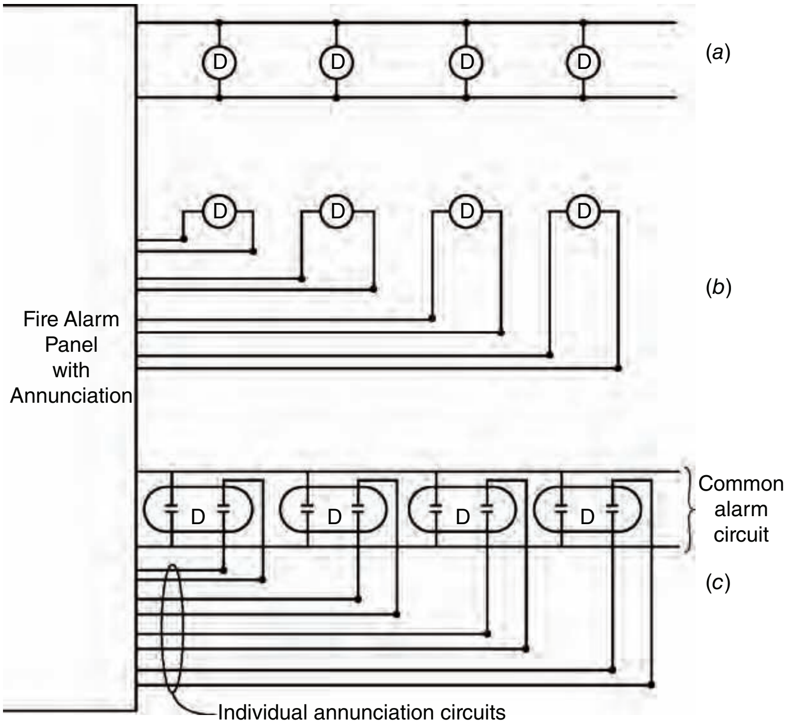


Fig. 25.39 *Identification of detectors, D, can be accomplished in three ways. (a) Each circuit, with multiple detectors, is annunciated as a zone. This arrangement is applicable where detectors are close together. (b) Each detector is wired individually, comprising a separate zone. This is applicable for large or scattered detector spacing. (c) Multiple detectors are wired on a single alarm circuit but individually annunciated. This is applicable where the number of detector circuits in the panel is limited, but individual detector identification is required.*

and, if the system is sufficiently large, annunciation can be provided. Audible devices are continuous ringing (vibrating) bells and horns. Visual devices are lights and strobes.

(b) Master-Coded Systems

This system, also called *common-coded* and *fixed-coded*, generates four rounds of code that are sounded and flashed on all of the building alarm devices when any signal-initiating device operates. It utilizes a single code transmitter at the panel. Normally, the system stops after four rounds of code, although it can readily be arranged to sound and flash continuously thereafter. When the code is set to ring bells at 108 strokes per minute, it is known as *march time* because of the rhythmic cadence. This beat aids in the rapid, panic-free evacuation of a building and therefore is frequently used in schools.

(c) Zone-Coded Systems

Identification of the alarmed zone in a system can be accomplished with zone lights, with an annunciator, or by coding. In the first two cases, it is necessary to *go to the panel or annunciator* to determine the location of the operated device, which entails a possibly critical delay. All coded systems avoid this drawback by sounding the code on all the gongs in a building, thus immediately identifying the station and permitting the building staff to quickly investigate the cause of the alarm and take appropriate measures.

If a *coded* system is desired, but by zone rather than by device (this is less expensive by far), *noncoded* manual stations are used, along with automatic detectors, grouped by circuit into zones or individually zoned (Fig. 25.39). Each zone circuit trips a zone's transmitters *in the panel*, which in turn ring the zone's code on single-stroke gongs or chimes. As with all coded systems, four rounds of coded signal are sounded, after which the system is silenced. In all coded systems, it is advisable to include a device that records all alarms in plain language, including the time of receipt and the code sounded.

(d) Dual-Coded Systems

This arrangement represents a combination of noncoded and zone-coded systems. When an alarm device operates, it initiates two separate functions—an identifying coded alarm and a continuous ringing evacuation alarm. The alarms are sounded simultaneously—the coded alarm in the building's maintenance office, and the evacuation alarm on separate audible and visual devices throughout the building. A requisite to the application of this system is a continuously staffed office in which the coded identifying signal can be received and acted upon.

(e) Selective-Coded Systems

These are fully coded systems in which all manual devices are individually coded and all automatic devices are arranged to trip code transmitters at the panel. Each manual station can be immediately identified by its distinctive code. Automatic devices may be grouped in any fashion desired and annunciated if desired. The combinations and circuitry are entirely in the hands of the designer. In large conventional systems, which fully selective-coded systems usually are, sprinkler transmitters and smoke detectors operate as integral subsystems of the main fire alarm panel.

(f) Presignaling

When it is desired to alert only key personnel, a system called *presignaling* is used. Small bells or chimes are activated only at their work locations. Because these systems are always selectively coded, the personnel alerted can immediately investigate and, if necessary, manually turn in a general alarm by key operation of a station. Because of the delay involved, this type of system is used only in buildings where evacuation is difficult and sufficient staff is available to immediately investigate the cause of an alarm.

25.13 SIGNAL PROCESSING

Once a hazard has been detected, a signal is transmitted to a fire control center and appropriate action taken. In conventional systems, the alarm signal is transmitted over dedicated conductors ("hard wiring") to a control panel, consisting of either electromechanical relays (in older systems) or solid-state switching circuitry (in modern systems). The control panel, in turn, actuates audible and visible device circuits, illuminates annunciator panels, controls fans and door releases, and so on, all via dedicated wiring. This arrangement has the advantages of reliability and simplicity. As a system grows, however, the wiring becomes heavy, complex, and expensive; panels become large and bulky; and changes become difficult. Also, troubleshooting of system faults becomes time-consuming. Furthermore, minimizing false alarms is problematic because alarm verification in systems with large zones containing many alarm devices is very difficult within the extremely short time span permitted for this operation.

As a result of these problems, a system was developed in which every device can be individually identified and remotely checked, without separate wiring to each. It is called an *addressable system* because all the devices are individually addressable.

25.14 ADDRESSABLE FIRE ALARM SYSTEMS

An addressable fire alarm system is, by definition, one that uses addressable fire detection devices, both automatic and manual. These detectors are essentially identical to conventional detectors except that they are equipped with electronic circuitry, usually mounted in a special base, that effectively makes each detector a separate zone. Thus, in the event of an alarm, the control can require alarm confirmation from an adjacent detector or can require a repeat alarm from the same detector after a remote reset.

Addressable devices are continuously polled from the control panel, and each replies to the poll by reporting its condition as OK–standby, alarm, or trouble. Because each device is identified by its address, an alarm or trouble signal from a detector can be quickly and easily confirmed. Detector identification is accomplished either visually on an annunciator panel or by alphanumeric readout on an LCD readout panel. Wiring is simplified; up to 100 detectors can be wired on a single multiplex line. Hardware costs of addressable systems are higher than those of a conventional system because of the additional electronics in the detector bases and the control panel. Maintenance costs, however, are somewhat lower because the panel's polling operation checks some (but not all) of a detector's electronics. Wiring costs for large systems are considerably lower than those of a conventional system. The process of measuring and calibrating detector sensitivity is essentially the same as in a conventional system; the detector must be physically demounted and checked. This can be a major expense in a large system because periodic sensitivity checks are mandated by NFPA codes.

25.15 ADDRESSABLE ANALOG (INTELLIGENT) SYSTEMS

Addressable analog systems are known in the fire alarm industry as *intelligent* despite the fact that the word *intelligent* is being used to refer to an inanimate device or system. To further confuse the issue, there is no accord among manufacturers on the exact meaning or use of the word when so applied. As a result, as of this writing, "very intelligent" and "extremely intelligent" devices have already appeared and other superlatives are sure to follow. The more accurate technical term *addressable analog* is used herein.

As mentioned previously, conventional and addressable detectors are identical except for the electronic identification coding of the latter. Both types test the adjacent space for temperature characteristics and/or products of combustion, compare the result to a preset threshold (adjustable), and latch into alarm position when the threshold is exceeded. The decision on whether to alarm is made at the detector, and the control panel acts only to receive the alarm signal and translate it into an audiovisual buildingwide alarm. Similar expensive periodic testing and adjustment of detectors in the field are necessary for both systems.

An analog detector gathers information from its sensor in analog form (voltage, current, or another variable characteristic proportional to the condition it senses) and transmits it to its control panel. That is, an analog detector acts only as a sensor; it does not make the threshold comparison leading to an alarm/no-alarm decision. That decision is made by a microprocessor at the control center. In modern systems, the data received from each detector are combined with other data—including reports from adjacent detectors, "historical" data on the condition of the detectors' time patterns at each detector that might falsely indicate an alarm, plus other relevant information. Analysis of all of this information leads to the decision on whether to sound a general alarm. This arrangement has these advantages:

- False alarms are sharply reduced because of the alarm verification procedures at the panel.
- Threshold sensitivity is set at the panel, permitting adjustment without accessing the detector.
- A history of each detector's output is recorded, and sensitivity degradation can be compensated for automatically. This decreases maintenance costs by increasing the time period between cleanings.
- Any malfunction of a detector is noted immediately at the control panel, since all detectors are polled every few seconds.

Some manufacturers place an integral microprocessor in *each* detector that is capable of performing almost all of the functions described previously as panel functions. These detectors act as normal addressable analog detectors, transmitting analog signals to a control panel. In the event of a connection failure, however, the on-board microprocessor converts the unit to a stand-alone, self-contained detector/controller.

25.16 AUTOMATIC FIRE DETECTION: INCIPIENT STAGE

Fire authorities agree that *most* fires pass through four stages, the last of which is the visible flaming fire. These stages are shown in Fig. 25.40 as a function of duration and degree of hazard. Also shown is the type of automatic detector recommended for detection at each stage.

In the incipient stage, the combustion products comprise a significant quantity of microscopic particles (0.01 to 1.0 micron), which are best

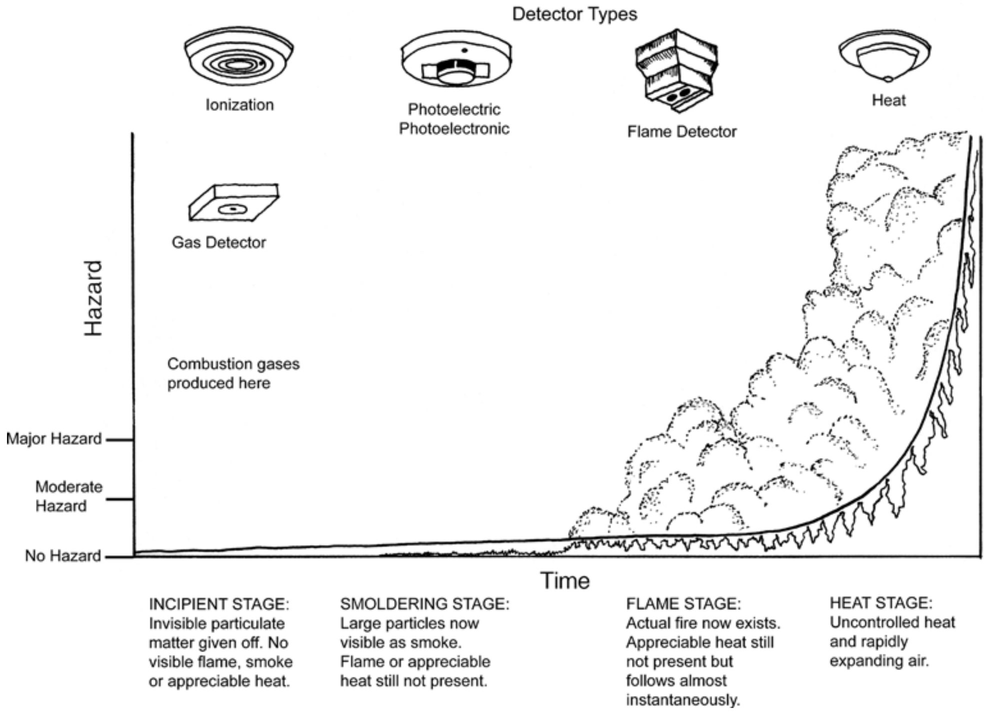


Fig. 25.40 *Four stages of a fire. Early detection of each stage requires a different type of detector that responds to a developing fire's evolving characteristics (fire signature). (Drawing by Amanda Clegg.)*

detected by *ionization-type* detectors (Fig. 25.41). These detectors contain a small amount of radioactive material that serves to ionize the air between two charged surfaces, causing a current to flow. Combustion particles entering the detector chamber reduce air ion mobility, thus reducing current flow and increasing voltage. These changes are sensed, and the alarm is set off.

The response time of this type of detector depends on how rapidly the combustion particles can reach the detector—a factor that varies with room air currents and with the type of material "burning." Once the particles reach the detector, the response is essentially instantaneous. Therefore, ionization detectors are best applied indoors, in spaces with stagnant air or low air velocity (below 50 fpm [0.25 m/s]) and in which little visible smoke (large particles) is expected. (Some manufacturers make a special unit whose sensitivity *increases* with air velocity for installation in spaces with air velocities of up to 500 fpm [2.5 m/s].)

Ionization detectors should not be installed on warm or hot ceilings, or in any other location where hot air concentrates, because the hot air

Fig. 25.41 *Addressable analog (intelligent) ionization-type smoke detector with an integral microprocessor that operates the unit's detection, diagnostic, and error-checking procedures. The detector is self-adjusting to compensate for sensitivity changes due to environmental conditions. Operating sensitivity is remotely adjustable from the control panel. (Photo courtesy of Cerberus Pyrotronics.)*

layer prevents the combustion particles from reaching the detectors. As a corollary, ionization detector sensitivity is higher at low ambient temperature.

Because ionization detectors react to minute particles of combustion, they should not be applied in, or close to, areas where normal activities produce such particles, as the result will be nuisance alarms. Thus, kitchens, bakeries, welding and brazing shops, workshops using open flames and burners, and areas with concentrated engine exhaust fumes are all inappropriate for application of this type of device. Ionization detectors respond best to fast-burning flaming fires. Because dust settling in the ionization chambers reduces sensitivity, the units need periodic cleaning and recalibration.

As can be seen in Fig. 25.40, the incipient stage of a fire also produces changes in the gas content of the environment. These combustion gases, which are not normally present in the air, are detectable by devices known as *gas-sensing fire detectors*. The principle of operation of these detectors depends upon the type. A semiconductor type reacts to a change in conductivity due to the presence of combustion gases, whereas a catalytic element type detects a change in the electrical resistance of the element caused by the presence of gases. Gas detectors are frequently used in conjunction with another type of detector so that both gases and particulate matter are detectable.

Coverage of incipient stage detectors varies from 150 to 900 ft^2 (14 to 83 m^2) per unit, depending upon the unit used, the type of combustible material in the space, and ambient conditions. Once a fire has passed the incipient stage and becomes smoky, an ionization detector loses sensitivity and photoelectric detectors are recommended. The same is true if, even in the incipient stage, the combustion products are the large particles typical of visible smoke. Ionization, gas, and photoelectric detectors are classified as early-warning types.

25.17 AUTOMATIC FIRE DETECTION: SMOLDERING STAGE

(a) Photoelectric Smoke Detection

The smoldering stage of a fire (see Fig. 25.40) is characterized by particles up to 10 microns in size. Such particles, although small, are visible to the naked eye as smoke and are best detected by photometric means. The simplest type of *photoelectric smoke detector* operates on the principle of beam obscuration, as shown schematically in Fig. 25.42. A beam of light is directed onto a photosensor, and a steady-state, no-smoke circuit condition is established. The presence of smoke in sufficient concentration partially obscures the beam, changing current flow in the photocell circuit and setting off an alarm response. Sensitivity is typically set at 0.5% to 4% obscuration per foot (0.3 m) for gray smoke and 0.5% to 10% for black smoke, to comply with UL Standard 268.

In this design, accumulation of dust and dirt and the presence of heavy fumes from industrial processes cause gradual obscuration of both the photo cell and the lamp. This, combined with lamp aging and consequent light reduction, results in *increased* sensitivity, causing false alarms that are not only a nuisance, but also can constitute a hazard. To correct this condition, continuous maintenance and periodic recalibration are necessary. This design is no longer recommended for spot-type smoke detection but is used in beam detectors, as discussed next.

(b) Projected Beam Photoelectric Smoke Detector

Beam-type photoelectric detectors (Fig. 25.43) consist of two separate units: a beam transmitter and a beam receiver, normally wall-mounted on opposite sides of a space, somewhat below the ceiling. They operate on the simple obscuration principle). They

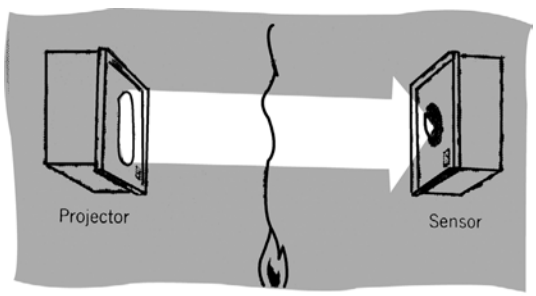


Fig. 25.42 *Principle of smoke detection by beam obscuration. This design is used in two ways: as illustrated, with a projector in one location and a photocell at a remote location, or with the entire assembly in a single small housing, with the light source and receiver on opposite sides of a 2- to 3-in.- (50- to 75-mm)-wide smoke chamber.*

Fig. 25.43 *This projected beam smoke detector utilizes an infrared (IR) beam so that ambient light will not affect its operation. Two sensitivity levels are available that are selected to match the distance between transmitter and receiver. Because heat attenuates or deflects the IR beam, the receiver translates this beam strength reduction as obscuration, identical to smoke obscuration. This effect makes the IR projected beam detector sensitive to high-heat flaming fires as well as smoky smoldering ones. (Photo courtesy of Notifier, a division of Pittway Corp.)*

are best applied in areas that do not lend themselves to the application of spot-type detectors. Among these are the following:

- High-ceiling areas such as atria, churches, malls, auditoriums, and the like. In these spaces, ceiling-mounted spot-type detectors present serious maintenance problems. This is particularly true in spaces such as theaters and auditoriums.
- Spaces with medium- to high-velocity airflow at the ceiling level. This condition severely dilutes smoke entering the test chamber of a spot detector. Although beam detectors are also negatively affected, their long throw and wide "vision" angle make the dispersion and dilution problems much less serious.
- Closed areas with little airflow, resulting in a hot air layer at the ceiling that prevents smoke from reaching ceiling-mounted spot detectors (Fig. 25.44). Exposed ceiling beams also tend to trap hot air and reduce the effectiveness of ceiling spot detectors.
- Environments that militate against spot detector use, such as those that are extremely dirty, corrosive, humid, very hot, or very cold. Beam-type detectors can be physically shielded against these conditions in a manner that interferes only minimally with their light-beam transmission and reception characteristics.

Beam-type detectors have an effective throw (from transmitter to receiver) ranging from 30 to 330 ft (9 to 100 m), depending upon ambient conditions, and can be spaced 30 to 60 ft (9 to 18 m) apart. This gives a coverage range of 900 to almost 20,000 ft^2 (84 to 1860 m^2), compared to spot detectors, whose *maximum* coverage is about 900 ft^2 (84 m^2). Furthermore, beam detectors are wall-mounted, which reduces maintenance problems.

Finally, beam detectors are usually drift-compensated (thus further reducing maintenance

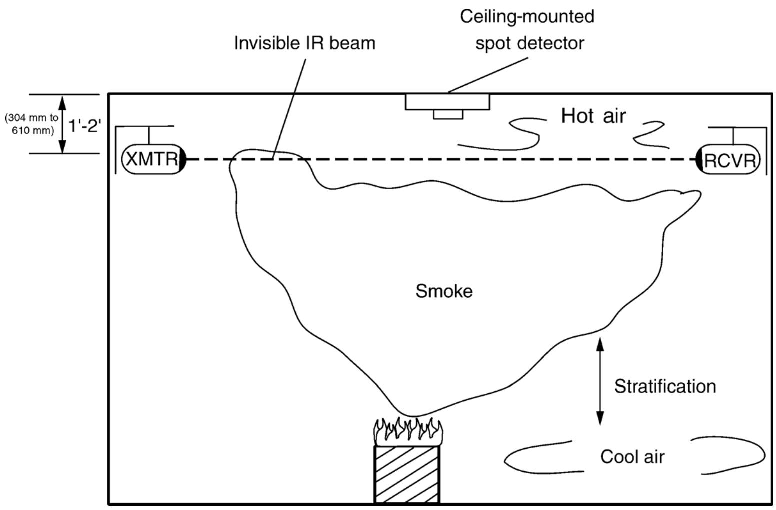


Fig. 25.44 *Stratification of air in a closed space leads to a concentration of hot air at the ceiling that can prevent smoke from reaching a ceiling-mounted spot smoke detector. A projected beam detector mounted 1–2 ft (0.3–0.6 m) below the ceiling will alarm due to obscuration, as shown.*

expense) and are arranged not to alarm with full obscuration, a condition that frequently occurs during routine building maintenance and repair work.

Disadvantages of beam-type detectors, compared to spot units, include:

- Response is to the second (smoke) stage of a fire, and therefore not in the same early-warning category as ionization or gas detectors.
- High cost.
- Inapplicable to spaces that lack an unobstructed view, as where pendant lighting fixtures, exposed ductwork, and the like are installed.

As with all types of detectors, the use of beam-type detectors in a particular application must be in accord with the requirements of *all* fire and administrative codes having jurisdiction in the particular locale.

(c) Scattered-Light Photoelectric Smoke Detector

A second design, usually referred to as a *photoelectronic*, *scattered-light*, or *Tyndall-effect* detector, is illustrated in Figs. 25.45, 25.46, and 25.47. In this design, a pulsed light-emitting diode (LED) beam is directed at a supervisory photocell, which serves to provide a baseline reference signal. The alarm photocell is shielded and normally receives no light

Fig. 25.46 *Addressable analog (intelligent) scattered-light-type photoelectric smoke detector with an on-board microprocessor that negates false-alarm signals caused by radio frequency and electromagnetic interference (RFI/EMI). It also validates trouble signals. If required, this unit can be equipped with a resettable heat detection element. The unit is approximately 5½ in. (140 mm) deep and 3 in. (75 mm) high. (Photo courtesy of Cerberus Pyrotronics.)*

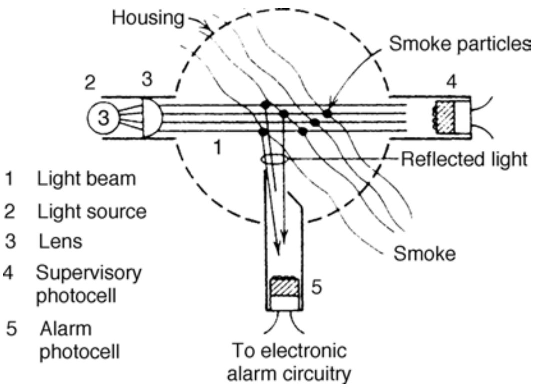


Fig. 25.45 *Principle of operation of a scattered-light photoelectronic spot smoke detector. A pulsed beam of light (1) from a source (2) is focused by a lens (3) on a supervisory cell (4). Smoke entering the unit reflects the light onto the alarm cell (5), changing its electrical characteristics and setting off an alarm. Photoelectric units with sensitivities of up to 2% per foot (0.3 m) are usually classified as early-warning units.*

Fig. 25.47 *This smoke detector, intended for duct mounting, can utilize either a photoelectronic or ionization-type head. The unit, which is usually mounted in return-air ducts rather than supply ducts to minimize smoke dilution effects, uses an air-sampling tube that extends across the full width of the duct. Duct smoke detectors are intended primarily to prevent smoke dispersal throughout a building by causing shutdown of the air-handling system and control of smoke damper operation. (Courtesy of Simplex.)*

from this beam. When smoke enters the unit, light is reflected from (scattered by) smoke particles and strikes the alarm cell. This changes the cell's resistance, and the resultant signal is amplified electronically, causing an alarm. An alternative design depends upon refraction of light to set off the alarm. These designs are not sensitive to normal dust and dirt accumulation or to light source depreciation, and high sensitivity can be maintained without continual maintenance. Thus, they are usually found in commercial and high-quality residential applications. Sensitivity is usually set at 1% obscuration per foot (0.3 m).

(d) Laser Beam Photoelectric Detector

A very-high-sensitivity laser diode source, scattered-light type photoelectric smoke detector has been developed that is classified by its manufacturer as an early warning device (Fig. 25.48). The high sensitivity results from the ability of the very sharply focused laser beam and its associated control panel software to differentiate between a smoke particle and a dust particle. It is best applied in clean environments.

(e) Air-Sampling Detection System

Another system that takes advantage of the high sensitivity of laser-beam-based photoelectric smoke detection is the air-sampling system (Fig. 25.49). In principle the system is quite simple. Instead of waiting for air that may be carrying incipient smoke particles to reach the detector(s) by thermal currents, this system samples air throughout the protected space by aspiration and brings it to the detector for testing. The aspiration and air conduction system is simply a piping system with holes at sampling points, and is powered by a fan. The advantage of the system is that air throughout the space is sampled, thus, in effect, converting each sampling opening into a highly sensitive laser-beam detector.

Because the piping can be zoned into manageable areas that can readily be checked for alarm verification, the disadvantage of nonaddressability of the aspirating openings is avoided. Addition of a microprocessor to a multizone control unit, which adjusts the alarm sensitivity of each zone based on a history of environmental smoke levels, all but eliminates false/nuisance alarms.

Fig. 25.48 This unit is an addressable analog laser-beam type of scattered-light photoelectric smoke detector. The sharply focused laser beam permits discrimination between smoke and dust particles, resulting in a high-sensitivity unit without false alarming. The unit is shown mounted on a sounder base containing a horn assembly, making it applicable to small, enclosed rooms. (Photo courtesy of Notifier, a division of Pittway Corp.)

(f) Application of Photoelectric Detectors

Photoelectric smoke detectors of all designs will detect particles from about 0.2 to about 1000 microns. Thus, they are useful not only for smoldering fires but also for the smoky fires that characterize the burning of certain plastics and chemicals. Also, particle agglomeration, which increases with the distance smoke travels, does not reduce their sensitivity, as it does with ionization types.

Maximum recommended spacing for photoelectric detectors, as for other types, is given by UL and Factory Mutual standards. Closer spacing is often mandated by the particular application or by the structure's characteristics. Manufacturers' recommendations should be obtained for all installations. In order to provide early-warning detection of a wider range of combustion products than is possible with either the photoelectronic or ionization-type detectors individually, several manufacturers produce a unit that combines a multichamber ionization detector with a photoelectronic detector.

25.18 AUTOMATIC FIRE DETECTION: FLAME STAGE

As noted in Fig. 25.40, the appearance of flame is followed almost instantaneously by heat buildup and the rapid spread of flame, with a large increase

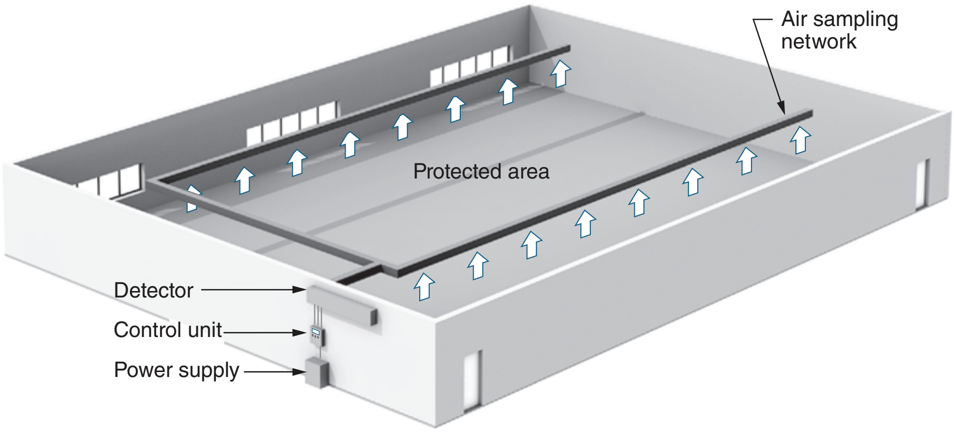


Fig. 25.49 *In an air-sampling system, air is aspirated at selected points in the protected area and piped to a highly sensitive laser beam photoelectric smoke detector for testing. Large areas are zone-piped so that trouble and alarm signals can be readily checked in the protected areas.*

in hazard. Detection of flame is not an "early warning," and the prime requirement for a detector at this stage is speed. The actions taken as a result of a flame detection alarm, such as fire suppression and/or evacuation, must also be very rapid. This is not the case with early-warning equipment alarms, which normally allow several minutes or more to investigate the authenticity of the alarm, *if desired*, before taking appropriate action.

Flame detectors are of two types: those that detect ultraviolet radiation and those that detect infrared radiation. Both types of radiation are present at the beginning of the flame stage.

Ultraviolet (*UV*) *radiation detectors* operate by optically detecting the UV radiation produced by flames, which is typically in the 170- to 290-nm range. (The entire UV range is 40 to 390 nm.) Hydrocarbon (organic material) fires in particular produce strong radiation in this range. A quartz filter in front of the UV sensor tube limits the detector's reception range to between 190 and 260 nm, which is below the visible spectrum. This desensitizes the detector to sunlight and to incandescent and fluorescent sources. The detector need not "see" a flame directly; it can also detect UV radiation reflected from walls, ceilings, and other objects. The more direct the path, the stronger the radiation and the more rapidly the detector will respond. Because many devices—in particular, electric welders—produce UV radiation in sufficient quantity to activate such a sensor, flame detectors are usually programmed to respond only to flickering sources at the usual flame flicker rate of 5 to 30 times per second.

In sum, UV detectors are long-range and very sensitive; they react in milliseconds and respond to most types of fires. They are best applied in highly flammable or explosive storage and work areas, either indoor or outdoor. Modern units are equipped with microprocessors that perform self-test diagnostics. UV detectors are best applied to detect hydrocarbon-fueled fires such as burning alcohol, methane, propane, acetone, and all types of petroleum products. Their principal disadvantage is that they are "blinded" by thick black smoke.

Infrared (*IR*) *radiation detectors* are sensitive to radiation in the IR region, between 650 and 6500 nm. Most commercial units are filtered to be sensitive to radiation in the 3800- to 4300-nm range and to have maximum sensitivity at 4300 nm (4.3 microns), which corresponds to the radiation emitted by hot CO_2. They differ from ambient heat detectors in that they respond to radiant energy and are essentially optical detectors. IR units have about half the distance range of UV detectors, are sensitive (although not as sensitive as UV detectors), react in seconds, and must be programmed for flicker response to avoid false alarms, which can occur if they are exposed to other sources of IR radiation, such as sunlight. Because of interference problems that cause false alarms, IR units are normally applied to enclosed spaces such as sealed storage vaults and the like. IR flame detectors are best applied to fires that result in rapid flaming combustion and the production of CO_2. Typical materials in this risk category are petroleum products, wood and paper products, coal, and plastics.

Combination UV/IR detectors, such as the one illustrated in Fig. 25.50, cover a wide range of risk applications, including aircraft hangars, fueling stations of all sorts, tank farms, and flammable storage areas. The illustrated unit contains a microprocessor that performs self-diagnostics, not only of the optical system but also of the electronic circuitry and calibration. The presence in a single unit of both UV and IR detectors permits the integral microprocessor to analyze the UV/IR ratio in any radiation detected and its time signature. This analysis is compared to known fire data in the microprocessor's memory in order to discriminate between actual fires and spurious radiation, thereby reducing false alarms.

25.19 AUTOMATIC FIRE DETECTION: HEAT STAGE

Again referring to Fig. 25.40, the heat stage is the last and most hazardous stage because, by this time, a fire is burning openly and producing great heat, incandescent air, and smoke. Spread of the fire depends upon fuel, air currents, and the construction of the space in which the fire is burning. Detectors intended for use at this stage respond to heat and are referred to as *heat-actuated, thermal, thermostatic*, or simply *temperature detectors*. They act much like the fusible link in a sprinkler head. Effective application is restricted to locations where the subsequent alarm permits adequate countermeasures to be taken in time to prevent injury and minimize loss. Keep in mind that the heat stage *follows* the smoke stage and that smoke, not heat, is responsible for most casualties in fires.

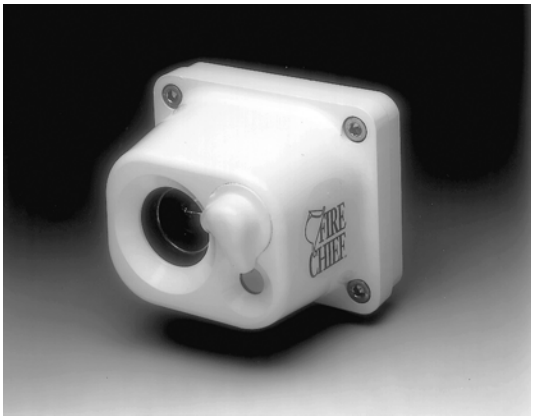


Fig. 25.50 *The combined ultraviolet-infrared (UV/IR) flame detector has peak sensitivity at 200 and 4300 nm, respectively, which corresponds to the maximum emission points of a typical hydrocarbon (e.g., petroleum products) fire. This unit is equipped with a microprocessor that performs diagnostic procedures and ensures proper calibration. The detector, which measures approximately $5 \times 5\frac{2}{3} \times 6$ in. ($127 \times 144 \times 152$ mm) deep is suitable for use in specific-class hazardous areas. (Photo courtesy of Meggitt Avionics.)*

Heat detectors have two designs: spot units, which are mounted in the center of the area that they protect, and linear units, which sense heat along their entire length. Both types respond to high ambient temperatures caused by hot air convection from a fire. The linear type can also sense the overheating of an object or surface with which it is in contact without the presence of fire.

(a) Spot-Type Heat Detectors

Spot heat detectors are of two types: fixed-temperature units and rate-of-rise units. In the former, a set of contacts operates when a preset (non-adjustable) temperature is reached—usually 135°F or 185°F (57°C or 85°C). The rate-of-rise type operates when the rate of ambient temperature change exceeds a predetermined amount (usually 15F°/minute [8C°/min]), which is indicative of the heat stage of a fire. The rate-of-rise unit is normally combined with a fixed-temperature unit in a single housing.

The fixed-temperature unit is available in either a one-time nonrenewable design, which utilizes a low-melting-point alloy plug, or an automatically resetting unit that operates in the same fashion as a thermostat. For most applications, a resettable unit is preferred. Spot units are best applied in spaces that are separated from occupied areas and are subject to rapid-temperature-rise fires. Three different designs of heat detectors are shown in Figs. 25.51, 25.52, and 25.53

(b) Linear Heat Detectors

In these devices, the entire length of a cable-like element is heat sensitive. This type of detector is applied to long, narrow elements, which are impractical to protect with spot detectors. Typical applications include cable trays, cable bundles of all sorts, conveyors, and large, long equipment. The heat-sensitive element is installed close to, or in direct continuous contact with, the protected item. As a result, any hot spot along the protected equipment will be detected.

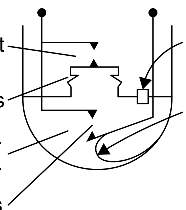
The detectors themselves are available in a number of designs. One type uses a pair of steel wires under tension, held apart by thermoplastic insulation (Fig. 25.54). When exposed to its rated alarm temperature, the insulation melts and the wires come into contact, changing the current flow in the circuit to which they are connected and setting off an alarm. This type is available in a range of alarm temperatures (155°F [68°C], 190°F [88°C], 280°F [138°C]) and can be used in open- or closed-circuit configurations in lengths of up to 2500 ft (760 m). Meters are available that indicate the exact point of a fault, so that in long runs where overheating rather than fire is detected, countermeasures can be taken rapidly, without the delay caused by having to seek out the fault point. The major disadvantage of this type of detector is that it is nonrenewable; once it has faulted, the melted section must be cut out and replaced.

Another type of linear detector is basically a linear thermistor—that is, a device whose electrical resistance varies with temperature (Fig. 25.55). The resistance is monitored at a control panel, and small changes are noted. Depending upon the thermistor material selected, the detection range can be set anywhere from 70°F (21°C) to 1200°F (650°C). This type of linear detector is more sensitive, rapid, and expensive than the preceding type. When linear detectors are installed in direct contact with the protected equipment, they detect surface temperature rather than air temperature and therefore act as early-warning devices. They are used extensively in this fashion to continuously monitor the surface temperature of such devices as transformers, switchgear, generators, and all sorts of hazardous equipment.

A third design for linear heat detectors uses optical fiber with a thermoplastic cladding (coating). Optical fiber transmits light by successive

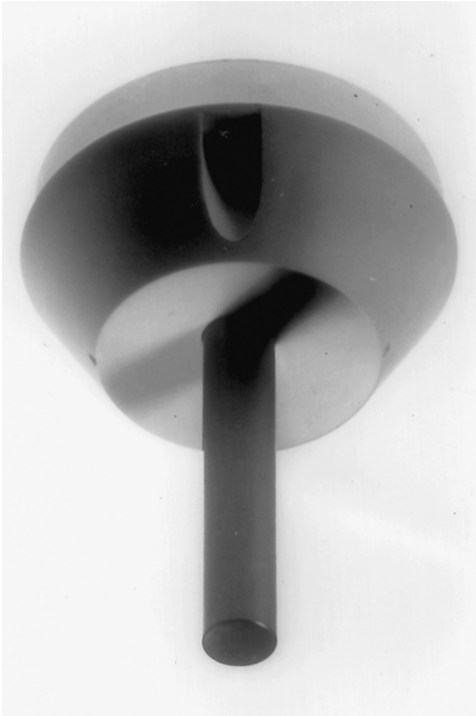
Fig. 25.51 *Detectors in the illustrated design are made with fixed-temperature, nonresetting elements that melt out at 130°F (54°C) or 200°F (93°C) and rate-of-rise elements that will alarm when the temperature rise is faster than 15F° (8C°)/minute. The illustrated unit is a 200°F (93°C) fixed-temperature-only model. It is applicable to spaces with unusually violent temperature fluctuations and ceiling temperatures between 100° and 150°F (37 and 65°C). (Photo courtesy of Cerberus Pyrotronics.)*

(*a*)

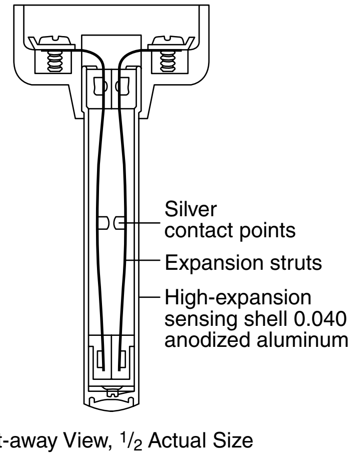


(*b*)

Fig. 25.52 *(a) A combination rate-of-rise and fixed-temperature detector. The detector and mounting plate fit on a standard 4-in.- (100-mm)-square outlet box. (b) The principles of device operation are shown schematically. The rate-of-rise unit consists of an air chamber with a restricted bleed valve. Rapid temperature rise causes the bellows to expand before air is lost by bleeding, thereby setting off the alarm. The thermostatic element is a fixed-temperature, self-restoring bimetallic unit.*



(a)



(b)

Fig. 25.53 *(a) A rate-of-temperature rise and fixed-temperature-type (135° or 200°F [57 or 93°C]) detector. Unlike the rate-of-rise detector in Fig. 25.52, this unit uses the principle of differential thermal expansion for both actions. (Photo courtesy of Cerberus Pyrotronics.) (b) Cutaway of a detector with a different base than that shown in (a). The detector consists of an aluminum tubular shell containing two curved expansion struts under compression fitted with a pair of normally open opposed contact points that are insulated from the shell. The tubular shell and the struts have different coefficients of expansion. When subjected to a rapid heat rise, the tubular shell expands and lengthens slightly. The interior struts lengthen but at a slower rate than the shell. The rapid lengthening of the shell pulls the struts together, closing the contact points and initiating the alarm. When subjected to a slow heat rise, the tubular shell and the interior struts lengthen at approximately the same rate. At the detector's set temperature points of 135°F or 200°F (57 or 93°C), the interior struts are fully extended, closing the contact points and initiating an alarm. (Drawing courtesy of Notifier, division of Pittway Corp.)*

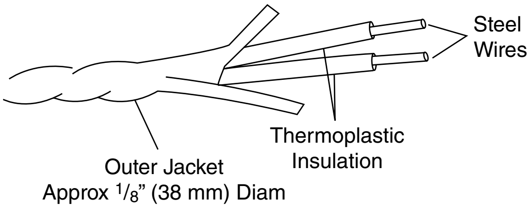


Fig. 25.54 *In this linear heat detector, the thermoplastic insulation on the stiff, twisted steel conductors melts, allowing the two conductors to touch and thereby register an alarm.*

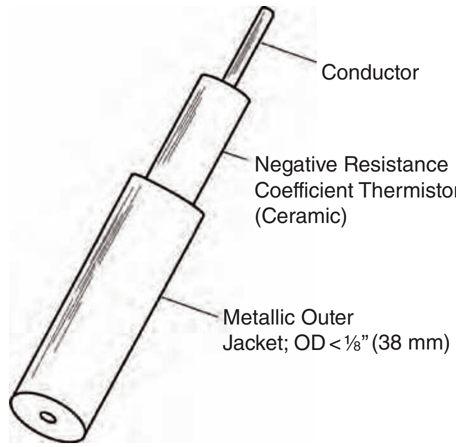
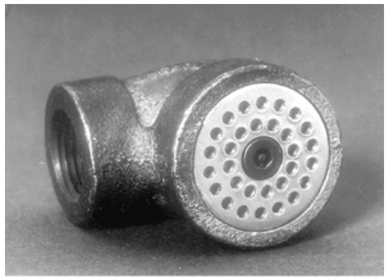


Fig. 25.55 *This linear heat detector is connected to an electrical control that monitors circuit current and thereby resistance. Any appreciable temperature rise along the entire cable length causes a sharp drop in the ceramic material's electrical resistance, which is immediately noted and pinpointed at the control point.*

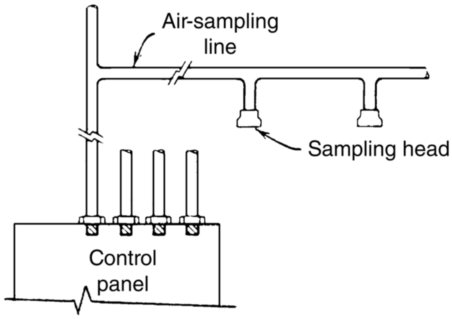
internal reflection at the fiber/cladding interface throughout the entire length of the fiber. Excessive temperature anywhere along the length of the fiber causes the cladding to melt and thereby appreciably changes the intensity of light received by the light sensor at the cable's end. This change is recorded and interpreted automatically as either a trouble signal or an overheat alarm signal. This design is available in lengths of up to 1 mile (1.6 km) or more. Other linear sensor designs include variable electrical resistance polymers, phase-change eutectic salt, and pneumatic tubing. Each type has its own advantages, drawbacks, and specific applicability.

Factors involved in the choice of a linear detector include:

- Physical characteristics and value of the protected elements
- Ease in locating the alarm area
- Requirements for resetting the system after an alarm
- Maintenance requirements
- Costs (first and life-cycle)



(*a*)



(*b*)

Fig. 25.56 *This very early warning system detects microscopic combustion products in air aspirated from the protected area, using a cloud chamber effect. (a) Tamperproof head housing, applicable to high-vandalism areas and correctional institutions. (b) Sampling heads are placed in all spaces to be monitored, including inside cabinets. (Courtesy of Protec Fire Detection, plc.)*

25.20 SPECIAL TYPES OF FIRE DETECTORS

Several other sophisticated detectors are available for early-warning detection during the incipient and smoldering fire stages. Among the most sensitive is a unit based on the operating principle of a *Wilson cloud chamber* (see Figs. 25.56 and 25.57). When microscopic particles, such as those produced by the early stages of fire, are introduced into a saturated atmosphere (cloud chamber), they act as nuclei around which water vapor condenses to form visible droplets. The detector operates by continuously sampling air from the protected space and setting off an alarm when the cloud chamber indicates the presence of particulate matter.

The continuous sampling procedure and the unit calibration make the system insensitive to dust and other noncombustion particulate matter and generally free of nuisance false alarms. The system's disadvantages are the need for piping and its high cost in small installations. For large installations (30 or more detection points), the cost is competitive with those of comparable systems. This detector is particularly applicable to high-value installations, such as museums, data-processing spaces, libraries, clean rooms, and facility control rooms, where its extremely high sensitivity may provide a critically important advance warning of an incipient fire.

25.21 FALSE ALARM MITIGATION

Smoke detectors are subject to false alarms due to moisture and particulate matter in the air. Technological advancement has reduced this problem; technology alone, however, will not entirely eliminate false alarms; the fire alarm system designer and the system user can contribute appreciably to minimizing annoying and potentially dangerous

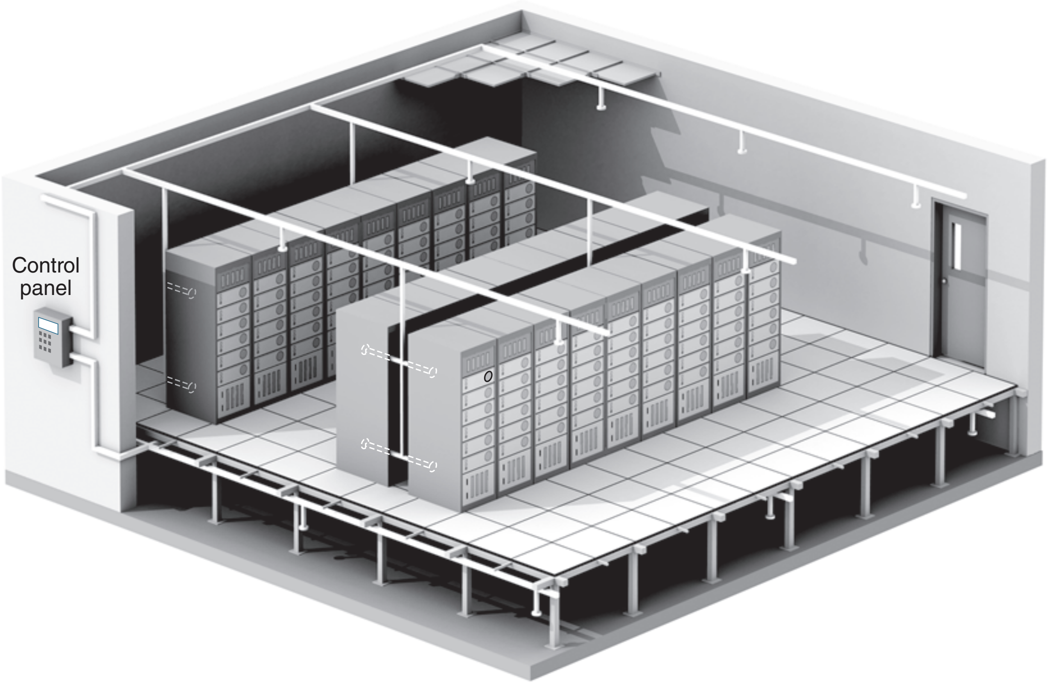


Fig. 25.57 Schematic diagram of a fire detection installation in a computer facility showing aspirating heads and piping. Note that air is sampled inside cabinets and under the raised floor in addition to sampling in the room itself.

false alarms by following some basic guidelines, including the following:

- Select appropriate smoke detectors. Choosing an ionization type where a photoelectric type is indicated, or vice versa, almost guarantees false alarms.
- Use detectors with drift compensation to permit accommodation of dirt/high temperature/humidity and air current ambient conditions, all of which increase false alarms.
- Where necessary, use radio-frequency interference (RFI) filters on detector circuits because line radio noise (spikes, surges) can cause alarms. This issue should be investigated in any installation with a heavy solid-state equipment load.
- Use control panels and detectors that have self-learning software and multispace-type algorithms that match sensitivity patterns to the spaces in which the detectors are installed.
- Use detector covers in areas where any type of construction work is taking place. This prevents fouling of detectors.
- When installing conventional systems, establish a regular maintenance and testing program that includes field testing and recalibration of all detectors.
- Avoid detector placement in areas where ambient conditions can cause problems. Where such placement is unavoidable, use compensating detectors, special maintenance routines, and appropriate verification procedures in the event of an alarm signal. These areas include:

1. Kitchens, laundries, boiler rooms, shower rooms, and other spaces with high humidity and steam
2. Repair shops, laboratories, and other areas where open flames are used in normal work
3. Garages and engine test facilities where exhaust gases are present
4. Smoking rooms and areas near spaces designated as smoking areas
5. Areas in which heavy accumulation of dust and dirt can be expected

6. Areas of high air movement, such as near loading docks and exit doors and near the discharge from diffusers or registers

25.22 MANUAL STATIONS

In contrast to automatic detectors, manual stations are operated by hand (Fig. 25.58). Manual stations can serve to spread an alarm that has already been detected by other means, either human or automatic. In conventional systems, manual stations are either *coded* or *noncoded*. (See Section 25.12 for an explanation of coding.) If identification of the exact manual noncoded station operated is desirable, an annunciation panel can be added to the system; this is equivalent to using each station as a noncoded indicating zone. Because of wiring costs, annunciated systems become expensive; beyond 10 stations, coding should be considered (see Fig. 25.39).

When the system design is such that immediate *buildingwide* aural identification of the operated station is necessary, a coded station is used. The station code is received at the control panel, processed, and then transmitted audibly on the system gongs. At least three rounds of code, and normally four rounds, are transmitted. The code usually comprises three or four digits (e.g., 2-3-2) with a pause between the ringing groups and a longer pause between the rounds. The first number may identify the building floor, the second digit the wing, and the third digit the individual station. Establishment of codes is left to the user.

Manual stations are placed in the normal path of egress from a building so that an alarm may be turned in by a person as he or she exits. It is *imperative*, therefore, that stations be well marked and easily found. Architects who place fire alarm stations in nooks and corners and in camouflaged cabinets because they spoil the decor of the lobby are defeating the purpose of the system. Similarly, placement of bells *inside* hung ceilings because they are unattractive is not only foolish but dangerous and should *never* be done, regardless of the circumstances. Loss of property and even of life may result from such ill-conceived aesthetic considerations.

Addressable manual stations obviate the necessity for a code wheel for each manual station but do not eliminate coding of alarm bells if buildingwide

(*a*)

(*b*)

(*c*)

Fig. 25.58 *(a) Manual fire alarm station with a break-glass rod. The unit is marked "local alarm," indicating that its operation will result in a buildingwide evacuation signal but not a city alarm. Similar units are equipped with multiple sets of contacts for annunciation and other control functions or with addressable system electronics. Other similar units use a lock-open design that requires a key to reset; this avoids the necessity of replacing the broken glass rod. (b) A manual station, which is normally surface-mounted, can be enclosed in a well-marked recessed cabinet if desired for aesthetic reasons. (c) This addressable manual station latches in the down (operated) position when pulled and can only be reset by key. The manual switch can be polled from the control panel to verify that it has indeed been operated and that the alarm signal is not a circuit malfunction. The station is semi-recessed and measures approximately 4 in. (100 mm) wide by 5½ in. (140 mm) high. (Photos courtesy of Notifier, division of Pittway Corp.)*

identification of the operated station is required. (Addressable manual stations are applicable only to addressable systems, not to conventional systems.) The purpose of gong coding is to permit rapid alarm verification by persons scattered about a building. An addressable manual station is identified only at the control panel, from which location a person must be sent to verify the alarm. In a small building, that is not a problem; in a large building, the time required to make such a verification is critical, because a manual alarm is already the result of a verified emergency, unless it is a deliberate false alarm. The decision, then, as to whether to code the gongs must be made on the basis of design decisions for a particular building. A typical addressable manual station is shown in Fig. 25.58*c*.

25.23 SPRINKLER ALARMS

Water flow switches are placed in sprinkler pipelines and operate when a sprinkler head goes off (Fig. 25.59). In electrical terms, a water flow switch is a set of contacts similar to a temperature detector. It can be used to trip a coded transmitter, setting off a sprinkler code; to show up on a sprinkler annunciator board, called a *sprinkler alarm panel*; or to act as a zone in a noncoded system. Wiring of water flow switches, or of switches activated by other extinguishing systems, is the same as that for a manual station.

Fig. 25.59 *Typical water flow indicator. The unit bolts onto a sprinkler pipe with the paddle inside the pipe. Any water motion deflects the paddle, causing a signal to be transmitted from the microswitch mounted in the box on top of the pipe. (Courtesy of Simplex/Potter.)*

25.24 AUDIBLE AND VISIBLE ALARM DEVICES

The type and placement of audible and visible alarms in a (public) building must meet the requirements of NFPA 72 (*National Fire Alarm and Signaling Code*) and the ADA (Americans with Disabilities Act). There are some disagreements between these requirements, as of this writing. In such cases, the fire alarm system designer, in concert with the building architect, should settle these differences to the satisfaction of the authority having jurisdiction.

(a) Audible Signals

Where an evacuation signal will be sounded throughout a building (public mode) to alert all of its occupants, the requirements of NFPA 72 are normally used because they are more stringent than those of the ADA. There are several requirements, the most important of which requires a minimum alarm sound pressure level of 15 dBA above the average ambient sound level or 5 dB above the maximum sound level (whichever is greater) for at least 1 minute. This means that the designer must actually measure or predict, with a high degree of accuracy, the anticipated sound levels in the various portions of a building. Average sound level estimates are available from many sources, including the NFPA code itself; maximum sound levels are not. As a result, most designers use a considerable factor of safety to ensure compliance. The upper limit permissible in any area is 120 dBA. See Chapter 22 for technical information on architectural acoustics and sound levels.

The minimum private mode requirement is the greater of 10 dBA above the average ambient level or 5 dBA above the maximum ambient sound pressure for at least 1 minute. Because this requirement generally applies to an enclosed space that houses the alarm panel or an adjacent space that is continuously occupied, the acoustic design is much simpler than for the public mode alarm.

The codes also specify the minimum required sound pressure levels for sleeping areas and mechanical equipment rooms, in addition to directives regarding the location of audible devices. The selection and placement of audible alarm devices is a technical task requiring acoustic analysis of spaces, occupancy, and the characteristics of available audible devices.

(b) Visible Signals

The requirements for these signals, the primary purpose of which is to alert hearing-impaired people, are covered in NFPA 72, UL 1971, ANSI 117.1, ADA, and various building code requirements. This is an area in which, at this writing, discrepancies exist between ADA requirements and those of NFPA 72, UL 1971, and ANSI 117.1 (which are in general agreement). All of the standards require that the visible alarm be a strobe light (usually a xenon flashtube), flashing at less than 2 Hz to minimize problems for persons with photosensitive epilepsy. This does not, however, solve this particular problem, because a person viewing light from more than one strobe (as at a corridor junction) can be exposed to a higher flash rate unless all strobes are synchronized. Careful strobe placement can help to minimize this problem.

(c) Strobe Intensity

For nonsleeping areas, the ADA requires a strobe intensity of 75 candelas (cd) and 50 ft (15 m) maximum unit spacing, whereas the other standards (UL, ANSI, NFPA) require an intensity dependent upon the size of the room. For sleeping areas, the ADA requirement remains the same, whereas the other standards require a 110-cd source if wall-mounted and a 177-cd source if ceiling-mounted. For corridors, the ADA requirement remains 75 cd at 50 ft (15 m) strobe spacing, whereas the other standards have a requirement that varies with corridor length.

Location of the strobes according to NFPA 72 must be such that the strobe light can be seen at any point in any space, regardless of the viewer's orientation, with the additional requirement that the maximum distance between strobes will not exceed 100 ft (30 m). A typical combination audiovisual fire alarm device is shown in Fig. 25.60.

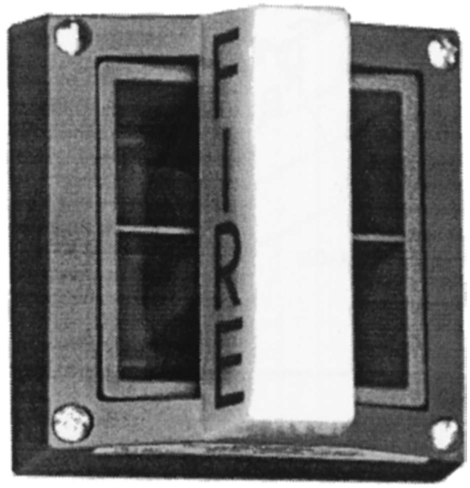


Fig. 25.60 *A combination audiovisual fire alarm signal is capable of sounding eight different warning tones that can be field selected. The 15-cd strobe flashes once every 1.5 seconds (2/3 Hz). The unit measures 4 in. (100 mm) square and can be mounted surface, semi-flush, or flush. (Photo courtesy of Notifier, a division of Pittway Corp.)*

25.25 GENERAL FIRE ALARM RECOMMENDATIONS

The specific building system descriptions that follow are based upon good present practice. Specific design decisions must meet the requirements of the latest edition of NFPA standards plus other codes having jurisdiction. Special attention is directed to Article 760 of the *National Electrical Code* (NFPA 70). It covers fire alarm system wiring in its broadest sense (i.e., "all circuits controlled and powered by the fire alarm system," including "fire detection and alarm notification, guard's tour, sprinkler . . . systems . . . safety functions, damper control and fan shutdown"). In office buildings the fire alarm system includes elevator capture and intercom, which, if powered and controlled by the fire alarm system, fall under Article 760.

25.26 RESIDENTIAL FIRE ALARM BASICS

Refer to NFPA 72 and NFPA 101 for detailed requirements. Residential occupancies include single-family residences, multi-unit complexes, and many-unit apartments. The alarm requirements for such a range of building types vary. In general, the system should provide sufficient time for the evacuation of residents and, in larger buildings, for appropriate countermeasures to be initiated. The elements of the system are the various alarm-initiating devices, the wiring and control panel, and the audible alarm devices. These are self-contained in small systems and assembled on site for large systems.

A good basic system for a multi-unit installation requires the following:

- A listed smoke detector: outside and adjacent to each sleeping area, in each sleeping room, at the head of every stair, with at least one on every level, including the basement. Combined smoke/heat detectors should be installed in the boiler room, kitchen, garage, and attic. Listed heat detectors in the attic, kitchen, and boiler room are frequently set at 185°F (85°C) because of high ambient temperatures. Other units are set at 135°F (57°C).
- An alarm in any detector produces an alarm in all audible and visual units.
- Control unit (central panel) is annunciated to show the location of an alarmed device and arranged to shut off oil and gas lines and the attic fan (to prevent the spread of smoke). Also, it should turn on lighting both inside and out, operate an automatic dialer to ring a neighbor's phone or a commercial central station, and give a distinctive alarm sound when the phone is answered. An outside bell and some other device that transmits an alarm outside the residence are important.
- Backup power for the system—a supervised storage battery with a trickle charger.
- Wiring of all devices connected to a system control unit should be on supervised circuits that will sound a trouble alarm in the event of a fault. The trouble alarm should be distinct from the fire alarm.

Additional requirements for detectors, alarms, power supply, supervision signals, and other relevant items—including special requirements for fire alarm systems that are combined with other signal systems—are found in the current edition of the previously referenced standards.

25.27 MULTIPLE-DWELLING ALARM SYSTEMS

The exact requirements for the location and type of detectors and their action are specified in NFPA 101 and NFPA 72. Multiple dwellings include apartment houses, dormitories, hotels, motels, and rooming houses. The prime directive for these structures in the event of a fire emergency is early warning and orderly egress, with consideration of the fact that a fire emergency may occur when most of the building's occupants are asleep. Design guidelines are as follows:

- Audible/visual alarms must be positioned so that all sleeping persons, including those with hearing and/or sight impairment, will be wakened. Code requirements for audible levels are minimum and are based upon average spaces and furnishings. Unusually large or oddly shaped spaces should be designed individually.
- Consider the possibility of living rooms being used as sleeping areas on a regular basis.
- Provide smoke detection in corridors, service spaces, and utility and storage rooms.
- Battery-powered detectors may not be used because, unlike homeowners, apartment dwellers rely on the building's management for all building services, and periodic battery checks and replacement might not be carried out.
- Provide standby power to all fire alarm circuits.
- All alarms should be identifiable, either by addressing or by annunciation. Annunciators should be located at the system control panel in the building management office or at the lobby desk in the case of hotels and dormitories. In all buildings, a lobby annunciator for the use of firefighters is advantageous.
- An alarm light over the door of each apartment or suite to indicate the location of an alarm is desirable. This is particularly important if the central panel only provides zone annunciation.
- In high-rise buildings, an emergency voice/alarm communication system should be provided.

25.28 COMMERCIAL AND INSTITUTIONAL BUILDING ALARM SYSTEMS

The requirements for these buildings are so varied that no specific recommendations can be made. A few suggestions, however, are in order:

- Presignaling, where permitted, is recommended for buildings that do not readily tolerate an evacuation alarm.
- In schools, particularly for the elementary grades, rapid, orderly evacuation of the building

is the primary requirement. Consideration must be given to the uniqueness of the sound of the fire alarm gongs to allow no possibility of confusion with program gongs where the latter are used. Also, because regular fire drills are mandatory in most schools, the system must be arranged to provide this capability.
- Public buildings should have an auxiliary alarm connection to the fire department.
- For medium-sized buildings, an accurate cost estimate frequently indicates an advantage of addressable analog systems over addressable systems because of the high detector maintenance costs of the latter. Similarly, addressable systems frequently have an economic advantage over hard-wired systems because of the high labor costs for wiring.

Figures 25.61, 25.62, and 25.63 show a few modern system control panels.

Fig. 25.61 *Conventional hard-wired eight-zone (maximum) solid-state fire alarm control panel for supervised Class A or Class B circuits. A single annunciator light indicates the alarmed zone. Alarm verification for each zone is provided. Both audible and visible alarms can be used on two alarm-signal circuits. The audible evacuation signal is a slow (20-BPM [beats per minute]) or fast (120-BPM) march time. Note the two standby batteries at the bottom of the cabinet. The unit measures approximately 16 in. (400 mm) wide and 17 in. (432 mm) high and is designed for surface mounting on 16-in. (400-mm) o.c. studs. (Photo courtesy of Simplex.)*

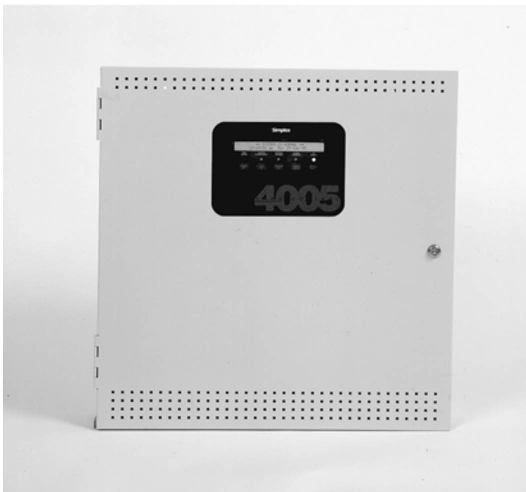


Fig. 25.62 *Control panel for a hard-wired conventional system that can accommodate up to 36 detection zones. The panel has a 2-line, 80-character alphanumeric display that indicates the zone alarm, trouble signals, and diagnostics information. The panel, which is 24 in. (610 mm) square, is microprocessor controlled and field programmable. A separate annunciator can be readily connected. (Photo courtesy of Simplex.)*

25.29 HIGH-RISE OFFICE BUILDING FIRE ALARM SYSTEMS

Sad experience has demonstrated that high-rise buildings, once thought to be fireproof, are emphatically not so. Indeed, due to their size, they have particularly severe fire protection problems, one of which is reliable communications during fire emergencies. As a result, fire codes now require that high-rise buildings be equipped with an emergency voice/alarm communication system. This system provides full control of transmission and building-wide distribution of all tones, alarm signals, and voice announcements on a selective or all-call basis. Specifically, it makes possible:

- Two-way active communications from the firefighters' control and command post (usually in the lobby) to at least one fire station per floor, all mechanical plant rooms, elevator machine rooms, and air-handling (fan) rooms.
- Distribution to selected areas of alert tones, signals, and prerecorded messages on independent channels. (A complete system of loudspeakers covering all areas of the building is an integral part of the system.)
- Communication with the fire department or central station.

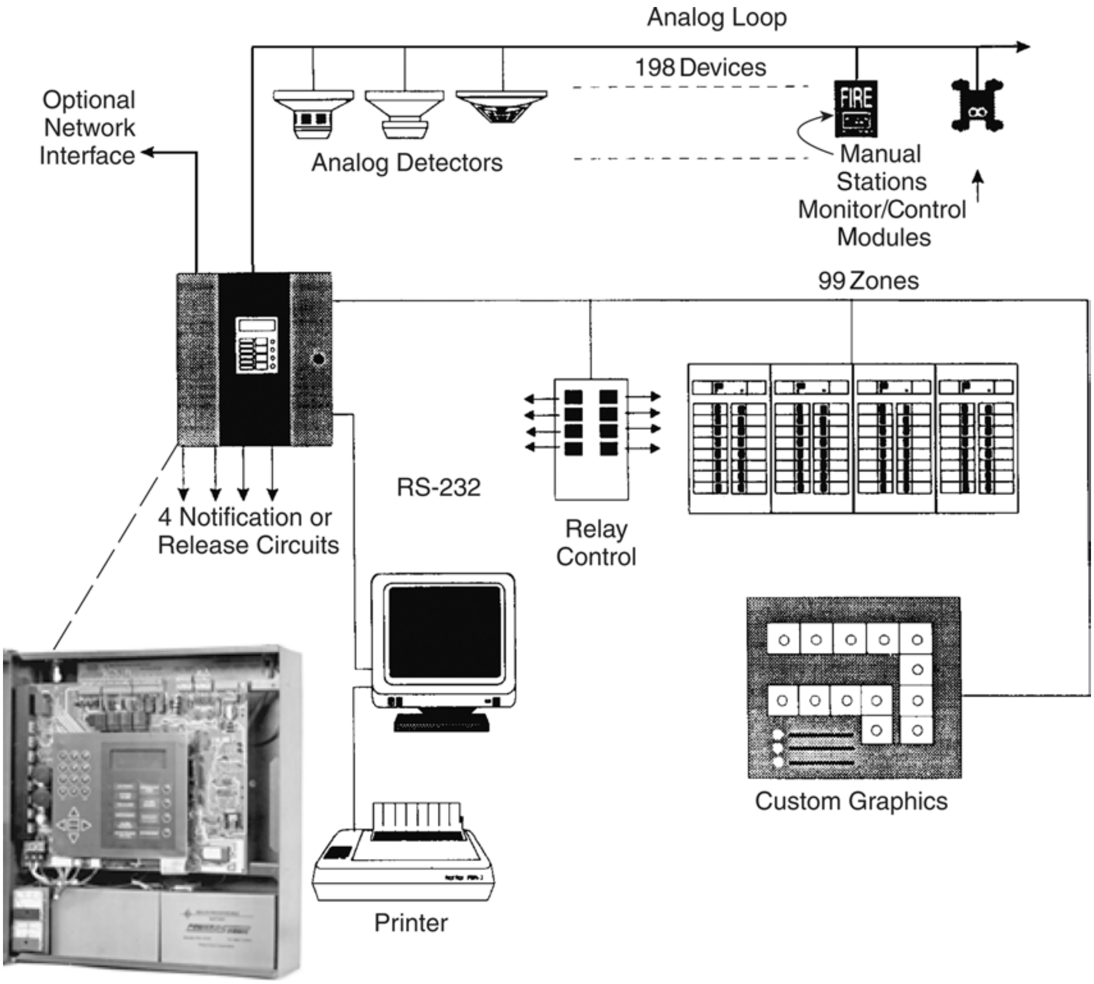


Fig. 25.63 System block diagram for a compact addressable analog fire system for a medium-sized building. The panel, which measures approximately 15 in. (380 mm) wide by 16 in. (400 mm) high by 6 in. (150 mm) deep, has a capacity of 99 analog detectors and 99 monitor/control modules. Integral programming provides drift compensation and sensitivity adjustment for analog detectors, detector maintenance (dirt accumulation) alert, and automatic cyclic sensitivity adjustment, plus standard diagnostics. Custom graphics and the video display can be arranged to display floor plans, device locations, and the like. Relay control can be used for control of the building's air-handling unit, elevator interlock, and security/access system interlock. Notification circuits connect to the central station, remote station, proprietary alarms, or municipal alarms. (Diagram courtesy of Notifier, a division of Pittway Corp.)

In addition to communication functions, the (lobby) fire command post provides:

- Visual display (annunciation) of all fire alarm devices, including sprinkler valves and water flow indicators
- Fire pump status indication
- Controls for any automatic stair door unlocking system (security access system)
- Emergency generator status
- Elevator location indicators plus operation and capture controls
- Control of smoke control devices (doors, dampers, etc.)
- Means for testing all circuits and devices

The exact equipment supplied depends upon the building and the local fire code. The distinctive characteristics of this system are the communications system, the visual display of alarm locations,

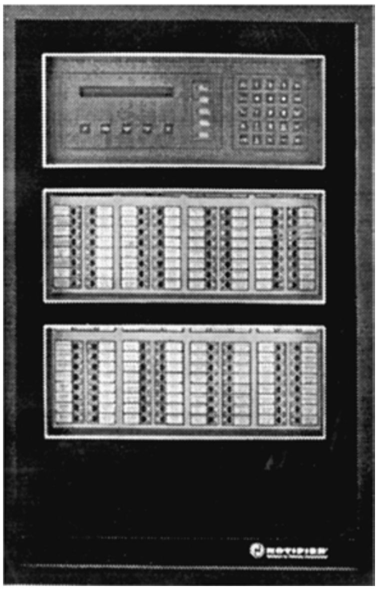


Fig. 25.64 *Large addressable analog (intelligent) fire alarm control panel, suitable for network connection, computer interface, and operation in conjunction with an emergency voice/alarm communication system of the type used in multistory office buildings (see Fig. 25.65). The unit can accommodate 990 analog detectors and an equal number of monitor/control modules. It is illustrated with a 96-point integral annunciator, and additional annunciation can be connected. The integral control panel provides for polling, diagnostics, sensitivity control of all detectors, automatic detector drift compensation, alarm verification, front-panel programming, and options for system connections, as shown in the block diagram of Fig. 25.63. (Photo courtesy of Notifier, a division of Pittway Corp.)*

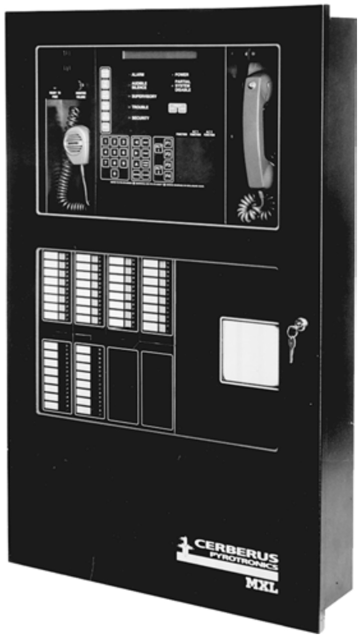


Fig. 25.65 *A multiplex emergency voice alarm/communication system panel used in large high-rise buildings in conjunction with the fire alarm system panel (Fig. 25.64). The panel controls and feeds a multiplexed voice alarm system, as well as strobe light circuits and a complete firefighter's telephone intercom. It provides evacuation, alert, page, and auxiliary signals to all building speakers selectively. An integral annunciator indicates which audio devices are connected to which of the three available audio channels. All audio risers are fully supervised and power limited. (Photo courtesy of Cerberus Pyrotronics.)*

and the remote control of air-handling equipment (Figs. 25.64 and 25.65).

25.30 INDUSTRIAL FACILITY ALARMS

In addition to manual stations at points of egress, these buildings use:

- Temperature and smoke detectors in storage areas and laboratories
- Smoke and flame detectors in record rooms and continuous process laboratories
- Water flow switches on all sprinklers

The annunciators, control panel, and alarm register are best placed in a guardroom. If none is available, an auxiliary or remote-station circuit should be added to allow remote monitoring.

Because of the high ambient noise level in many plants, horns are substituted in such areas for bells and gongs, which might be inaudible.

In summary, the specific occupancy recommendations given here are representative of good current practice. Codes, however, are constantly being changed in this particularly sensitive field, and they vary with project locale. In actual design situations, all codes and regulations having jurisdiction must be complied with.

References and Resources

Numerous standards from NFPA, UL, ANSI, HUD, and the ICC dealing with fire alarm systems are presented in Section 25.7

Egan, M. D. 1978. *Concepts in Building Firesafety*. John Wiley & Sons. Hoboken, NJ.

ICC. 2012a. *International Building Code*. International Code Council. Washington, DC.

ICC. 2012b. *International Fire Code*. International Code Council. Washington, DC.

Jensen, R. (ed.). 1975. *Fire Protection for the Design Professional*. Van Nostrand Reinhold. New York.

NFPA. 2008. *Fire Protection Handbook*, 20th ed. National Fire Protection Association. Quincy, MA.

NFPA. 2010. NFPA 750: *Standard on Water Mist Fire Protection Systems*. National Fire Protection Association. Quincy, MA.

NFPA. 2012. NFPA 92: *Standard for Smoke Control Systems*. National Fire Protection Association. Quincy, MA.

NFPA. 2013. NFPA 10: *Standard for Portable Fire Extinguishers*. National Fire Protection Association. Quincy, MA.

NFPA. 2013. NFPA 13: *Standard for the Installation of Sprinkler Systems*. National Fire Protection Association. Quincy, MA.

NFPA. 2013. NFPA 14: *Standard for the Installation of Standpipe and Hose Systems*. National Fire Protection Association. Quincy, MA.

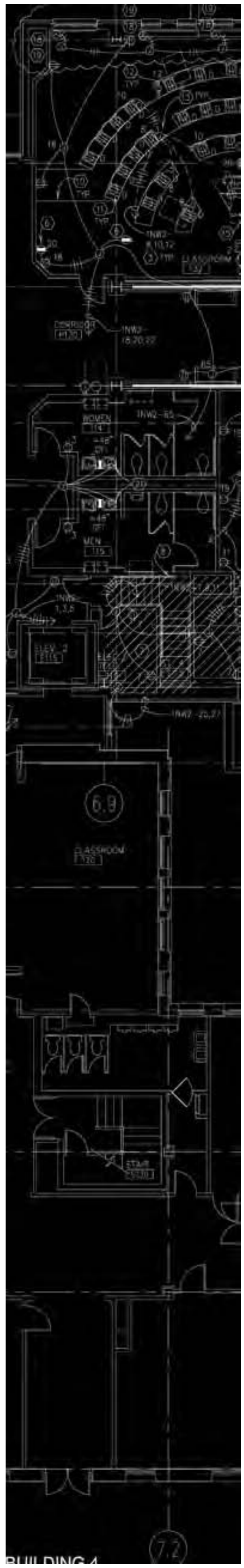
NFPA. 2014. NFPA 780: *Standard for the Installation of Lightning Protection Systems*. National Fire Protection Association. Quincy, MA.

UL. 2007. UL 96A, *Standard for Installation Requirements for Lightning Protection Systems*. Underwriters Laboratories, Inc. Northbrook, IL.

U.S. Architectural and Transportation Barriers Compliance Board. *Americans with Disabilities Act (ADA) Accessibility Guidelines for Buildings and Facilities.* Washington, DC.

PART VII

ELECTRICITY



Electricity is the most prevalent form of energy in a modern building. It not only supplies electric outlets and electric lighting, but also provides the motive power for HVAC equipment, traction power for elevators and material transport, and power for all signal and communications equipment. An electric power failure can paralyze a facility. Such power failures often occur at a district or regional scale, beyond the control of a building designer. A properly designed facility can, however, quickly return to partial operation through the action of emergency equipment that can furnish part of the facility's electricity needs for a limited time.

Given the complete dependence upon electric power for normal operation that is characteristic of most modern buildings, designers must be familiar with the basic concepts and equipment of normal electrical systems. Chapter 26 reviews basic electrical relationships, with emphasis on electric circuits, power, energy, energy costs, and methods of energy management and electric load control. Chapter 27 describes electrical service, utilization, and emergency/standby power equipment. Also addressed are energy conservation considerations and economic factors. Chapter 28 introduces the concept of electrical equipment ratings and capacity, and continues with a description of modern wiring systems and their components. Chapter 29 draws on information given in the three preceding chapters to demonstrate straightforward design methods for building electrical systems. Chapter 30 presents information on photovoltaic (PV) systems, which are being increasingly adopted as part of green, net-zero-energy, and carbon-neutral building design solutions.

CHAPTER 26

Principles of Electricity

HISTORICALLY, USABLE ENERGY WAS most often produced by burning a fossil fuel such as coal or oil. The resultant energy output was used directly as heat and/or light or converted by machines into motion. Only since the end of the nineteenth century, however, has this heat in turn been used to create another very usable form of energy—electricity. Nuclear reactors, geothermal resources, and concentrating solar collectors may also be used to produce heat for electricity generation. Hydropower is an interesting example of non-heat-based generation. Fuel cells and photovoltaics produce electricity directly (with heat as a waste product). It is well to remember that, in terms of consumption of fuel resources, electricity is an expensive form of energy because the efficiency of the overall heat-to-electricity conversion, on a commercial scale, rarely exceeds 40%.

26.1 ELECTRIC ENERGY

Electricity is a form of energy that occurs naturally only in unusable forms such as lightning and other static discharges or in natural galvanic cells (which cause corrosion). The primary problem in the utilization of electric energy is that, unlike fuels or even heat, it cannot be readily stored and therefore must be generated and utilized in the same instant. This requires an entirely different concept of utilization than, for example, a heating system with its fuel source, burner, piping, and associated equipment.

The bulk of electric energy utilized today is in the form of *alternating current* (AC), produced by AC generators commonly called *alternators*. *Direct-current* (DC) generators are utilized for special applications requiring large quantities of DC. In the building field, such a requirement was once almost universal for elevators because of the ease with which DC motors can be speed-controlled. Today, however, because fine speed control of AC motors is practical, AC motors are the driver of choice for modern elevators, with attendant energy savings and a reduction in machinery space requirements. Smaller quantities of DC, furnished either by batteries, photovoltaic (PV) equipment, or rectifiers, are utilized for telephone and signal equipment, controls, and other specialized uses.

26.2 UNIT OF ELECTRIC CURRENT—THE AMPERE

Electricity flowing in a conductor is called *current*, which is measured in *amperes*, abbreviated *amp*, *amps*, or simply *A*. When current is expressed in an equation, it is usually represented by the letter *I* or *i*.

It is convenient to establish an analogy between electrical systems and mechanical systems as an aid to understanding the characteristics of electricity. Current is a measure of flow and, as such, corresponds to water flow in a hydraulic system (Fig. 26.1). The analogy is not complete, however, because in a hydraulic system the velocity of water

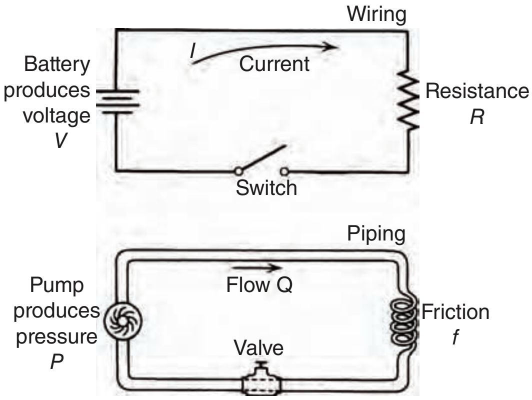


Fig. 26.1 *Electric-hydraulic analogy. The circuits show that voltage is analogous to pressure, current to flow, friction to resistance, wiring to piping, and switches to valves.*

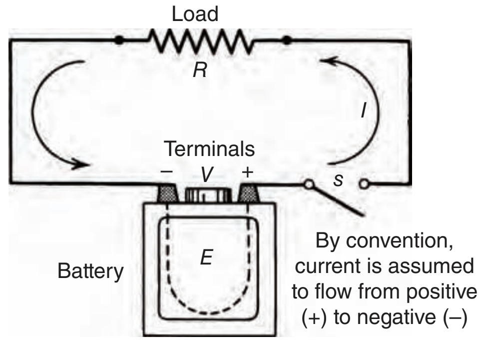


Fig. 26.2 *Current flows in the electric circuit as a result of the voltage (potential difference) V that exists between the terminals of the battery. By convention, current direction is from positive (+) to negative (–) in the circuit (and from – to + inside the battery).*

flow can vary, whereas in an electrical system the velocity of (electric) propagation is constant and may be considered instantaneous.

26.3 UNIT OF ELECTRIC POTENTIAL—THE VOLT

The movement of electrons (and its associated energy, which constitutes electricity) is caused by creating a higher positive electric charge at one point on a conductor than exists at another point on the same conductor. This difference in charge can be created in a number of ways. The oldest and simplest method is by electrochemical action, as in a battery.

In the ordinary dry cell, or in a storage battery, chemical action causes positive charges (+) to collect on the positive terminal and electrons—i.e., negative charges (−)—to collect on the negative terminal. Assume for the moment that nothing is connected to the battery terminals. There is a tendency for flow between the electrified particles concentrated at the positive and negative terminals. *Potential difference* or *voltage* is the name given to this tendency, or force. It is analogous to pressure in a hydraulic or pneumatic system. Just as the pressure produced by a pump or blower causes water or air to flow in a connecting pipe, the potential (voltage) produced by a battery (or generator) causes current to flow in a conductor connecting the terminals between which a voltage exists (Fig. 26.2). The higher the voltage (pressure), the higher the current (flow) for a given resistance (friction). Other means of producing voltage, both direct (DC) and alternating (AC), are discussed in Section 26.8. The unit of voltage is the volt, abbreviated *V* or *v*.

26.4 UNIT OF ELECTRIC RESISTANCE—THE OHM

The flow of fluid in a hydraulic system is resisted by friction; the flow of current in an electric circuit is also resisted. In a DC circuit this force is called *resistance* and is abbreviated *R*; in an AC circuit it is called *impedance* and is abbreviated Z. The unit of measurement is the *ohm*. The scientific convention of naming units after persons whose work is closely related to the field is followed here. Thus, the units ampere, volt, and ohm are derived from André Ampère, Alessandro Volta, and Georg Ohm.

Materials display different resistances to the flow of electric current. Metals generally have the least resistance and are therefore called *conductors*. The best conductors are the precious metals—silver, gold, and platinum—with copper and aluminum being only slightly inferior. Conversely, materials that resist the flow of current are called *insulators*. Glass, mica, rubber, oil, distilled water, porcelain, and certain synthetics exhibit nonconductive properties and are used to insulate electric conductors. Common examples are rubber and plastic wire coverings, porcelain lamp sockets, and oil-immersed switches.

26.5 OHM'S LAW

The current I that will flow in a DC circuit is directly proportional to the voltage V and inversely proportional to the resistance R of the circuit. In AC circuits, the same relation holds true except that instead of DC resistance, impedance is used. Expressed as an equation, this is the basic form of Ohm's law:

$$I = \frac{V}{R} \tag{26.1}$$

Ohm's law is frequently written in another form:

$$V = IR \tag{26.2}$$

which expresses the mathematical relationship that voltage is the product of current and resistance. This form has no intuitive or logical basis; therefore, remembering the form of Equation 26.1 will prove more useful. It clearly states the physical situation, that is, as a result of voltage V, a current I is produced that is proportional to the electric voltage (pressure) V and inversely proportional to the electric resistance (friction) R. If V increases, I will increase; if R increases, I will decrease.

Example 26.1 illustrates the application of Ohm's law. The example chosen is applicable to both AC and DC because the load device is purely resistive. When a load is purely resistive, resistance and impedance are equal. This is more fully explained in the subsequent discussion of alternating current.

EXAMPLE 26.1 An incandescent lamp having a hot resistance of 66 ohms is put into a socket that is connected to a 115-V supply. What current flows through the lamp (after it reaches operating temperature)?

SOLUTION

$$I = \frac{V}{R} = \frac{115 \text{ volts}}{66 \text{ ohms}} = 1.74 \text{ A}$$

(These values correspond to a typical 200-W general service incandescent lamp.) ■

Hot resistance is mentioned in Example 26.1 because the electrical resistance of some materials changes with temperature. A typical example of this is a tungsten-filament lamp that when first turned on (cold) accepts, for a fraction of a second, 10 to 15 times the steady-state hot filament current.

26.6 CIRCUIT ARRANGEMENTS

The two basic electric circuit arrangements are *series* and *parallel*. These concepts are the same for both DC and AC. As previously, the discussion focuses upon purely resistive circuits so that calculations are applicable to both DC and AC. In other than purely resistive circuits, AC circuit calculations are different and much more complicated than those for their DC counterparts.

(a) Series Circuits

In a series arrangement the elements are connected one after another, that is, in series. Thus, resistances and voltages add. This is indicated graphically in Fig. 26.3. An electric circuit may be defined as a complete conducting path that carries current from a source of electricity to and through some electrical device (or load) and back to the source. A current cannot flow unless there is a complete (closed) circuit. Due to the arrangement of components in a series circuit, *the current is the same in all*

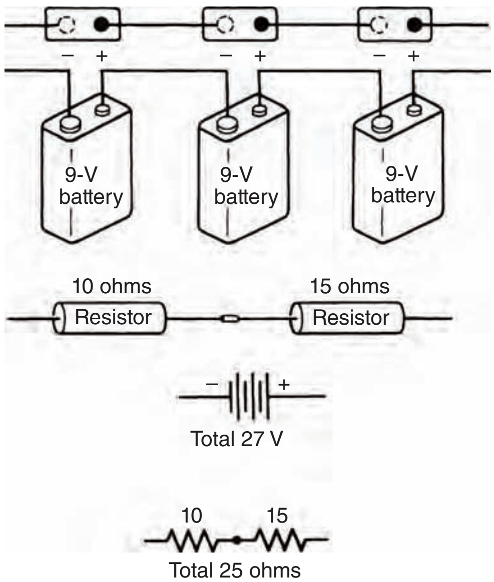


Fig. 26.3 Physical and graphic representation of a series connection of batteries and resistors.

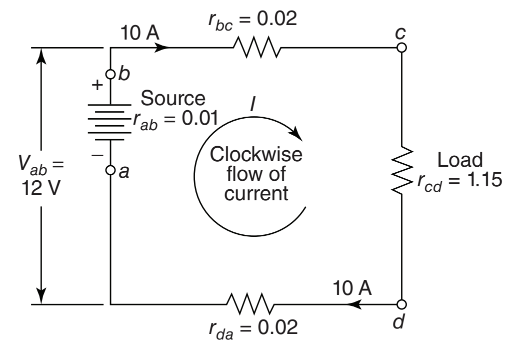


Fig. 26.4 *A series circuit always contains a voltage source (here, the battery), and a load (R). This circuit also shows the resistance of the connecting wires for accuracy. Such resistances are normally neglected because they usually are very small compared to the load resistance.*

parts of the circuit. A somewhat more complicated circuit is shown in Fig. 26.4 and is analyzed in Example 26.2.

It is customary to refer to connection points on wiring diagrams by letters, as a, b, c, d, and so on. The battery voltage may then be called V_{ab} = 12 V; the voltage across the load resistance, V_{cd} = 11.5 V; and the resistance of the two wires $r_{bc} + r_{da}$ = 0.04 ohm. The positive and negative terminals of the battery are always shown.

EXAMPLE 26.2 The battery in Fig. 26.4 is rated at 12 V; the total line resistance (the total for both wire segments) is 0.04 ohm; the battery internal resistance is 0.01 ohm; and the load resistance is 1.15 ohms. Determine (a) the current flowing in the circuit and (b) the voltage across the load (V_{cd}).

SOLUTION

(a) The current flowing is

$$I = \frac{V}{R} = \frac{V_{ab}}{r_{ab} + r_{bc} + r_{cd} + r_{da}}$$

$$= \frac{12}{0.01+0.02+1.15+0.02} = \frac{12}{1.2} = 10 \text{ A}$$

(b) The voltage drop across the load is

$$V_{cd} = I \times R_{cd} = 10 \times 1.15 = 11.5\ V$$ ■

Series circuits find very limited application in building wiring because failure of any one load (such as a burned-out lamp) will open the circuit (shutting off power to all loads on the circuit).

(b) Parallel Circuits

When two or more branches with loads are connected between the same two points, they are said to be connected in *parallel* or *multiple*. Such a parallel arrangement and its hydraulic equivalent are shown in Fig. 26.5. In the circuit of Fig. 26.6 it can be seen that the voltage across each load is the same, but the current in each load (branch) depends upon the resistance of that load. Parallel loads, in effect, constitute separate circuits. In this arrangement the total current in the circuit is the sum of the individual currents flowing in the branches—that is,

$$I_T = I_1 + I_2 + I_3$$

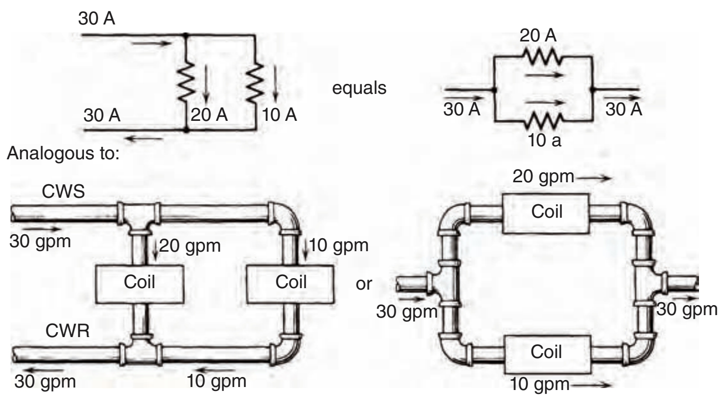


Fig. 26.5 *In a parallel connection the flow divides between the branches, but the pressure is the same in each branch.*

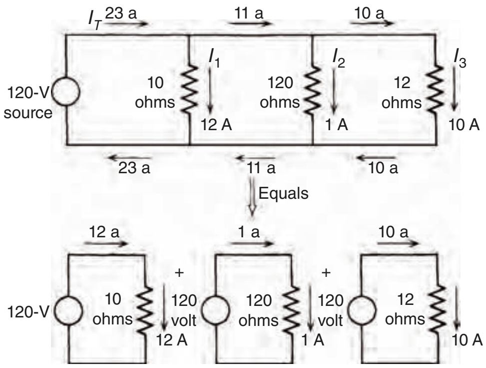


Fig. 26.6 *Note that loads connected in parallel are equivalent to separate circuits combined into a single circuit. Each load acts as an independent circuit unrelated to, and unaffected by, the other circuits.*

Notice in Fig. 26.6 that the total current flowing in the circuit is the sum of the currents in all the branches, but that the current in each branch is determined by a separate Ohm's law calculation. Thus, in the 10-ohm load, a 12-A current flows, and so forth.

The parallel circuit is the standard arrangement in all building wiring. A typical lighting and receptacle arrangement for a large room is shown in Fig. 26.7. Here the lighting fixtures constitute one parallel (multiple) grouping, and the convenience wall outlets constitute a second parallel grouping. The fundamental principle to remember is that loads in parallel are additive for current and that each load has the same voltage across it.

One additional point is important to appreciate. Remember from Ohm's law that current is inversely proportional to resistance. Thus, as resistance drops, current rises. Now look at the circuit of Fig. 26.7. Normally, that circuit carries the (vector) sum of the currents in the two branches. (Vectorial addition is discussed in Section 26.11, Example 26.5c.) If, by some mischance, such as deterioration of the wiring insulation, a connection forms between points a and b, the circuit is *shortened* so that there is no resistance in parallel branch ab. The current rises instantly to a very high value, and there is a *short circuit*. If the circuit is properly protected, a fuse or circuit breaker opens and the circuit is deenergized. If not, the heat generated by the very high current will probably start a fire.

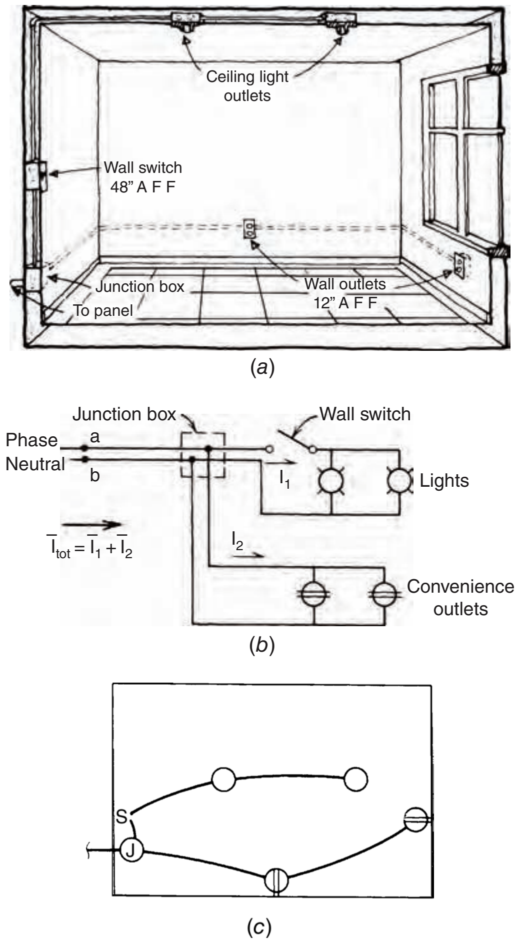


Fig. 26.7 *Parallel groupings of ceiling lamp outlets and wall outlets are in turn connected in parallel to each other. The circuit is shown (a) pictorially, (b) schematically, and (c) as on an electrical floor plan. The horizontal bar over the currents I_1 and I_2 in (b) signifies the use of vectorial addition (see Example 26.5).*

26.7 DIRECT CURRENT AND ALTERNATING CURRENT

A flow of electric current that takes place at a constant time rate, practically unvarying and in the same direction around a circuit, is called a *direct current* (DC or dc). Figure 26.8 shows DC voltages of 1.5 V positive polarity and 1.0 V negative polarity.

When the flow of current is periodically varying in time and in direction, as indicated by the symmetrical positive and negative loops, or *sine waves*, in Fig. 26.9, it is called an *alternating current* (AC or

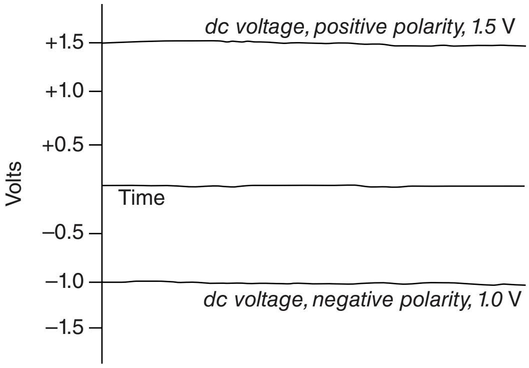


Fig. 26.8 *Graphic representation of DC voltages with positive and negative polarity.*

ac). The distance along the time axis spanned by a positive and a negative AC loop is called *one cycle*. The number of such cycles occurring in 1 second is known as the *frequency* of the AC current. Modern AC systems in the United States and Canada operate at a frequency of 60 cycles per second, or 60 *hertz* (after Heinrich Hertz). Thus, current at 60 hertz (abbreviated Hz) is delivered to the consumer. In Europe and much of Asia, 50-Hz distribution is standard.

An AC circuit differs from a DC circuit in a number of important respects and, because the normal current supply to a building is 60 Hz AC, it is important to understand AC terminology and usage. Instead of resistance, the corresponding parameter in an AC circuit is *impedance*, which is (also) measured in ohms.

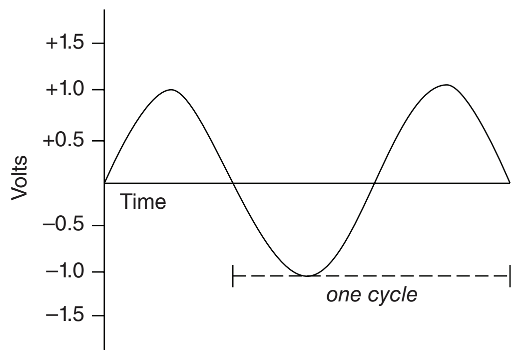


Fig. 26.9 *Graphic representation of a pure single-frequency alternating current (AC). The figure shown is a sine wave. Note that a complete cycle includes both the positive and negative loops. The number of full cycles in 1 second is defined as the frequency of the current (or voltage).*

Depending upon the circuit load, impedance can be markedly different from the DC resistance. For an AC circuit, Ohm's law is

$$I = \frac{V}{Z} \tag{26.3}$$

where Z is the symbol for impedance. This book does not go into AC circuit calculations, primarily because such calculations are not especially useful to the typical building designer. What *is* useful and important is an understanding of power and energy in both DC and AC circuits. These concepts are discussed in the following sections.

26.8 ELECTRIC POWER GENERATION—DC

With respect to the generation of large amounts of DC power, piezoelectric and thermoelectric effects can be ignored. Photovoltaic power generated from PV modules—as discussed in Chapter 30—is becoming increasingly important as a practical source of electricity for specialized uses and as part of green/carbon-neutral building design efforts. This leaves the battery and the DC generator (along with PV) as everyday sources of DC electricity. Because the DC generator is in reality an AC generator with a device (commutator) attached that rectifies the AC to DC, the battery is the major direct source of DC. (There are some special types of generators that produce DC *directly*, but their use to date has been extremely limited.) A discussion of the application of batteries for emergency and standby power supplies can be found in Chapter 29.

Another source of DC power is rectification of AC. This can be accomplished on any desired scale to provide as much DC power as there is available AC power. The principal application of DC in older buildings is for elevator motors. In many buildings DC is used for standby power. Small amounts of DC are also used for controls and telephones.

26.9 ELECTRIC POWER GENERATION—AC

Alternating current is produced commercially by an AC generator, generally called an *alternator*. Its prime mover may be any type of engine or turbine. The process by which electricity is produced is illustrated in Fig. 26.10; it is based upon the

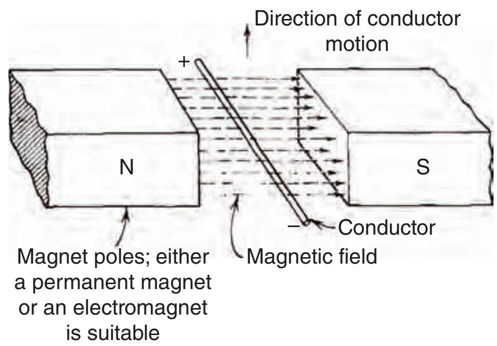


Fig. 26.10 *The action fundamental to all generators. When a conductor of electricity moves through a magnetic field, a voltage is induced in the conductor, with polarity as shown.*

fundamental discovery in 1831 by Michael Faraday of the principle of electromagnetic induction. Briefly, this principle states that when an electrical conductor is moved in a magnetic field, a voltage is induced in the conductor. The direction of movement determines the polarity of the induced voltage, as shown in Fig. 26.10.

If a conductor is formed into a coil and rotated in a magnetic field, a voltage of alternating polarity is produced—that is, alternating current. It does not matter whether the conductor or the magnet moves; the motion of the conductor and the field

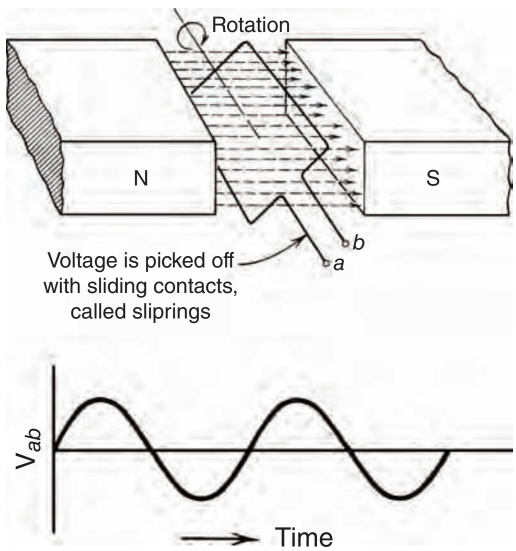


Fig. 26.11 *Rotating a coil in a magnetic field produces an alternating sinusoidal voltage at terminals a and b because of the alternating polarity.*

with respect to each other produces the voltage (see Fig. 26.11). It is only one step (that of commercial development) from this rudimentary AC generator to the large, powerful alternator that produces AC in a modern power plant. The frequency of the voltage generated is a function of the machine design and the speed at which it is driven. Normal generator frequency in the United States, as noted previously, is 60 Hz, whereas in Europe and the Mideast it is 50 Hz.

26.10 POWER AND ENERGY

It is critically important that the distinction between power and energy be clearly understood. All too frequently the terms are used interchangeably—which is incorrect and can lead to bad design decisions. *Energy* is the technical term for the more common expression *work*. *Power* is the rate at which energy is used. For example, it takes a fixed amount of energy to lift a weight a given distance either quickly (in 5 minutes) or slowly (over five hours), but the faster it is lifted, the more power is required. Energy is the product of power and time, that is,

$$\text{energy (work)} = \text{power} \times \text{time} \tag{26.4}$$

In practical terms, energy is synonymous with fuel consumption and, therefore, with cost (and resource depletion, for fossil fuels). Energy can be expressed as barrels (liters) of oil, cubic feet (cubic meters) of gas, tons (kilograms) of coal, kilowatt-hours of electricity usage, and/or dollars of fuel cost. The outcome of energy efficiency efforts for buildings can be stated in terms of annual usage of oil, gas, and electricity or, alternatively, in terms of dollars spent for fuel or utilities. In technical terms, energy is expressed in units of Btu (calories), foot-pounds (joules), and kilowatt-hours. Conversion factors between these (and other) units of energy are found in Appendix A. In terms of fuel, 1 kilowatt-hour (kWh) of energy is roughly equivalent to 0.5 lb (0.23 kg) of coal, 0.07 gal (0.26 L) of oil, 7.7 ft^3 (0.22 m^3) of natural gas, and 8200 gal (31,000 L) of water in a hydroelectric dam.

Power is the rate at which energy is used or work is done (energy and work being synonymous). The term *power* implies continuity—that is, the use of energy at a particular rate, over a given, generally considerable, span of time. The concept of power necessarily involves the factor of time because it is, as stated previously, the *rate* at which work is done. Multiplying power by time yields energy consumption. Typical units of power in the I-P system are horsepower, Btu per hour, watt, and kilowatt. In the SI system, the corresponding units are joule per second, calorie per second, watt, and kilowatt. In physical terms, power is also the rate at which fuel (energy) is used. Thus, power can also be expressed as gallons (liters) of oil per hour, cubic feet (cubic meters) of gas per minute, and tons (kilograms) of coal per day. (When using fuel figures, it is important to ascertain the assumed fuel-to-useful-energy conversion efficiency. When not stated, "energy content" [i.e., energy availability at 100% conversion efficiency] is assumed.) Most U.S. building codes are based upon site energy use, rather than source energy—making conversion efficiency a hidden (but important) issue.

26.11 POWER IN ELECTRIC CIRCUITS

The unit of electric power is the watt (W); 1000 watts is the commonly encountered kilowatt (kW). Both units are commonly used in building design situations depending upon the magnitude of the load—as in a 100-W incandescent lamp, or a 5-kW resistance heating coil. The power input in watts to any electrical device having a resistance *R* and a current *I* is given by the equation

$$W = I^2 R = (I)\,(IR) \tag{26.5}$$

where *W* is wattage. This is true for both DC and AC circuits. Because the resistance of a device or load is generally not known, whereas the circuit voltage and current are known, it would be preferable to be able to calculate power using these latter two quantities. This can be done, but differently for DC and AC.

In DC circuits, by Ohm's law, $V = IR$ and, because $W = I\,(IR)$ from Equation 26.5, we obtain

$$W = VI \tag{26.6}$$

where
W is watts
R is ohms
I is amperes
and *V* is volts

In AC circuits, impedance consists of a combination of DC resistance and AC resistance (called *reactance*). Reactance causes a phase difference between voltage and current. This phase difference is represented by an angle, the cosine of which is called the *power factor* (*pf*). Power factor is extremely important in that it enables us to calculate power in an AC circuit. The AC power equation is similar to that for DC (see Equation 26.6) with the addition of the AC power factor term; that is,

$$W = VI \times pf \tag{26.7}$$

If *pf* is not included in the equation, the product of voltage and current gives a quantity known as *volt-amperes*. In a purely resistive circuit, such as one with only electric heating elements, impedance equals resistance, power factor equals 1.0, and wattage equals volt-amperage. In other circuits this is not the case. A few examples should help make the application of these equations clear.

EXAMPLE 26.3 Referring to Example 26.1, calculate the power drawn using Equations 26.5, 26.6, and 26.7.

SOLUTION

Because an incandescent lamp is purely resistive and therefore has unity (1.0) power factor, it does not matter whether the circuit is AC or DC.

From Example 26.1,

$$R = 66 \text{ ohms},\ I = 1.74 \text{ A},\ V = 115 \text{ V}$$

1. In a DC circuit, we would use Equation 26.6:

$$W = VI = 115 \times 1.74 = 200 \text{ W}$$

2. In an AC circuit, we would use Equation 26.7:

$$W = VI \times pf = 115 \times 1.74 \times 1.0 = 200 \text{ W}$$

3. In either a DC or an AC circuit, we can use Equation 26.5:

$$W = I^2 R = (1.74)^2 \times 66 = 200 \text{ W}$$

■

EXAMPLE 26.4 Using the data given in Example 26.2 and Fig. 26.4, determine (a) the power loss in the wiring and (b) the power input to the load.

SOLUTION

(a) The total power loss in the wiring is

$$W = I^2 R = I^2(r_{bc} + r_{da})$$
$$= (10)^2 \times 0.04 = 4 \text{ W}$$

(b) The power taken by the load is

$$W = I^2 R = I^2 R_{cd} = (10)^2 \times 1.15$$
$$= 115 \text{ W (or 0.115 kW)}.$$

Alternatively, we can find this power by multiplying voltage and current. The voltage on the load is

$$IR = 10 \times 1.15 = 11.5 \text{ V}$$

and

$$W = VI = 11.5 \times 10 = 115 \text{ W (or 0.115 kW)}$$ ■

EXAMPLE 26.5 Refer to Fig. 26.7. Assume a 150-W incandescent lamp at each ceiling outlet. Also assume the load connected to one convenience outlet to be a 10-A hair dryer with a power factor of 0.80. Calculate the current and power in the two branches of the circuit, and the total circuit current, assuming a 120-V AC source.

SOLUTION

(a) In the circuit branch feeding the lamps, the power consumption is for two 150-W lamps; that is,

$$P = 2\ (150) = 300 \text{ W}$$

To calculate the current, we would use Equation 26.7, which expresses power in an AC circuit:

$$W = VI \times pf$$

Because incandescent lamps are effectively resistive loads, their power factor is 1.0. Therefore:

$$\text{Power} = VI$$
$$300 \text{ W} = 120 \text{ V} \times \text{I}$$
$$\text{I} = \frac{300 \text{ W}}{120 \text{ V}} = 2.5 \text{ A}$$

(b) In the second branch, we have a 10-A, 0.8-*pf* load.

$$\text{Power in watts} = \text{volts} \times \text{amperes} \times \text{power factor}$$
$$W = 120 \times 10 \times 0.8 = 960 \text{ W}$$

However, the branch volt-amperes are

$$V \times A = 120 \times 10 = 1200 \text{ VA}$$

This latter figure is important for sizing electrical equipment.

(c) To calculate the total current flowing from the panel to both branches of the circuit, we must combine a purely resistive current (lamp circuit) with a reactive one (dryer circuit). The exact value of the current is the *vectorial* sum of the two branch currents, which calculates to be 12.1 amperes. (Vectorial addition is a technique that considers the phase angle between two currents. Phase angle, or phase difference, was explained previously.) In normal circuit design practice, the *arithmetic* sum of 12.5 amps would be used. The error introduced is only 3.2%, and because it results in slightly oversized circuit components, it is on the safe side. Only where power factors are very low would a designer use vectorial addition to more accurately size a circuit. ■

One further example will demonstrate the importance of power factor in normal situations.

EXAMPLE 26.6 The nameplate of a single-phase motor shows the following data: 3 hp, 240 V, AC, 17 A. Assume an efficiency of 90%. Calculate the motor (and therefore circuit) power factor.

SOLUTION

From Appendix A the conversion 1 hp = 746 W is found. Therefore,

$$3 \text{ hp} = 3 \times 746 = 2238 \text{ W}$$

This represents the motor *output*. Because for any device

$$\text{efficiency} = \frac{\text{output}}{\text{input}}$$

then

$$\text{power input} = \frac{2238 \text{ W}}{0.9} = 2487 \text{ W}$$

However, for AC,

$$\text{power} = \text{volts} \times \text{amperes} \times \text{power factor}$$

so

$$2487 \text{ W} = 240 \text{ V} \times 17 \text{ A} \times \text{power factor}$$

and

$$\text{power factor} = \frac{2487}{240 \times 17} = 0.61$$

Note the large difference between volt-amperes and watts:

$$V \times I = 240 \times 17 = 4080 \text{ VA}$$
$$P \text{ (as before)} = 2487 \text{ W}$$

where P designates power. This difference is important in circuit design, as will be seen in the discussion of methods for sizing circuit components. ■

26.12 ENERGY IN ELECTRIC CIRCUITS

Because energy = power × time, the amount of energy used is directly proportional to both the power of a system and the length of time it is in operation. Because power is expressed in watts or kilowatts and time in hours (seconds and minutes are too small for practical use), the units of energy used are watt-hours (Wh) or kilowatt-hours (kWh).

EXAMPLE 26.7

(a) Find the daily energy consumption of the appliances listed if they are used for the length of time shown.

Toaster (1340 W)	15 min
Coffee maker (500 W)	2 h
Fryer (1560 W)	½ h
Iron (1400 W)	½ h

(b) Assuming that the average cost of energy is \$0.12 per kilowatt-hour, find the daily operating cost.

SOLUTION

(a) Toaster: 1340 W = 1.34 kW × ¼ h = 0.335 kWh

Coffee maker: 500 W = 0.5 kW × 2 h = 1.00 kWh

Fryer: 1560 W = 1.56 kW × ½ h = 0.78 kWh

Iron: 1400 W = 1.4 kW × ½ h = 0.70 kWh

Total 2.815 kWh per day

(b) The daily operating cost is 2.815 kWh × \$0.12/kWh = \$0.3378 (say, 34 cents). ■

The power used by a residential household varies with the time of day. A graph showing the power used by a typical American household during a normal weekday might look something like the one in Fig. 26.12. The *average* power demand of the household is much lower than the *maximum*. The ratio between the two is called the *overall load factor* and runs between 20% and 30% for a typical household. The energy used by this household for the 24-hour period is represented by the *area* under the curve of Fig. 26.12. This can be determined only by integration because it varies continuously. Such integration is exactly what a kilowatt-hour meter does, as explained in Section 26.15 (dealing with electrical measurements).

EXAMPLE 26.8 It has been estimated that the average power demand of an American household with an electric stove is 1.8 kW. Calculate the monthly electric bill of such a household, assuming a flat rate of \$0.12 per kilowatt-hour.

SOLUTION

Monthly energy use:

$$1.8 \text{ kW} \times \frac{24 \text{ h}}{\text{day}} \times \frac{30 \text{ days}}{\text{month}} = 1296 \text{ kWh per month}$$

Monthly electric bill:

$$1296 \text{ kWh} \times \$0.12/\text{kWh} = \$155.52$$ ■

In Example 26.8 the bill was based on a *flat* rate of 12 cents per kWh. Flat rates are very common for residential users. In the U.S., residential rates vary from a low of 5–6 cents per kWh in states using substantial hydroelectric power to as high as 17 cents per kWh in some Northeastern states. Hawaii has the highest rates in the U.S. The difficulty in making blanket statements regarding the cost-effectiveness of any proposed energy efficiency investment is illustrated by this 3:1 range in electricity costs.

Electric utilities (by franchise agreement) must provide for a customer's *maximum* power demand, whereas the monthly energy billing only compensates them for *average* demand, which is always lower. One technique used by electric utilities to account for this condition is to levy a *demand charge* for short-term power (kW) requirements in addition to the normal energy (kWh) billing for overall consumption. This technique has long been standard for industrial and commercial user rates, but it is still unusual for residential users. The demand charge is

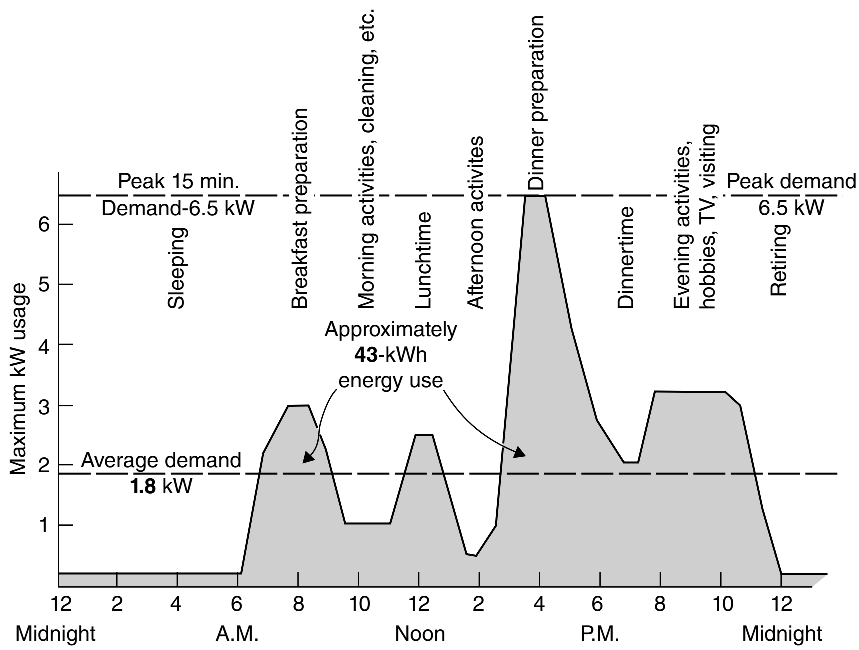


Fig. 26.12 *Hypothetical graph of power usage for a typical U.S. household. Electric cooking is assumed. The area under the curve represents energy usage. Maximum kW demand (vertical axis) is based on a 15-minute integrated demand, thus eliminating spikes in demand, such as those caused by starting a refrigeration (air-conditioning) compressor. This curve has a 24-hour use of approximately 43 kWh, giving an average 24-hour demand of 1.8 kW. The ratio between this average demand and the peak demand of 6.5 kW is called the load factor, which here is 27.5%.*

especially useful as a means of encouraging users to reduce their peak loads. In so doing, energy use is also somewhat reduced. As utilities continue to adjust to deregulation and rapidly fluctuating fuel costs, and incur difficulties meeting growing demands for service, expect to see more innovative (and complex) billing schemes being implemented.

26.13 ELECTRIC DEMAND CHARGES

Electric utility companies normally levy a kW demand charge on all but individual residential and a few special-category customers. Varying with the utility company involved, this monthly charge runs between \$2 and \$15 per kW of maximum average demand in any demand interval for a given month. Demand intervals vary, usually being either 15 or 30 minutes (see Fig. 26.13).

Many utilities use a *sliding window* interval timing technique that starts a new interval every minute and updates the maximum interval demand accordingly. This enables them to find and bill for the maximum electric power demand in any 15- or 30-minute period in a month. Some companies also include a *ratchet* clause that levies a demand charge for a number of months based upon the maximum demand in any single month. This penalizes users with seasonal highs—that is, users with a low *yearly* load factor. The load factor is a measure of uniformity of power demand; a low load factor indicates short-time demand peaks for which the user is heavily charged. The justification for the imposition of a demand charge and the significance of load factors can best be demonstrated by an example.

Assume that a pottery manufacturer, whose average 8-hour daily load is 20 kW for lighting and pottery wheels, operates two 50-kW electric kilns twice a month for a 4-hour period each time. Further assume an energy charge of \$0.10 per kWh. The total monthly *energy* bill for the operation of the two kilns would be

$$\text{energy cost} = 2 \times 50\ \text{kW} \times 8\ \text{h} \times \frac{\$0.10}{\text{kWh}} = \$80$$

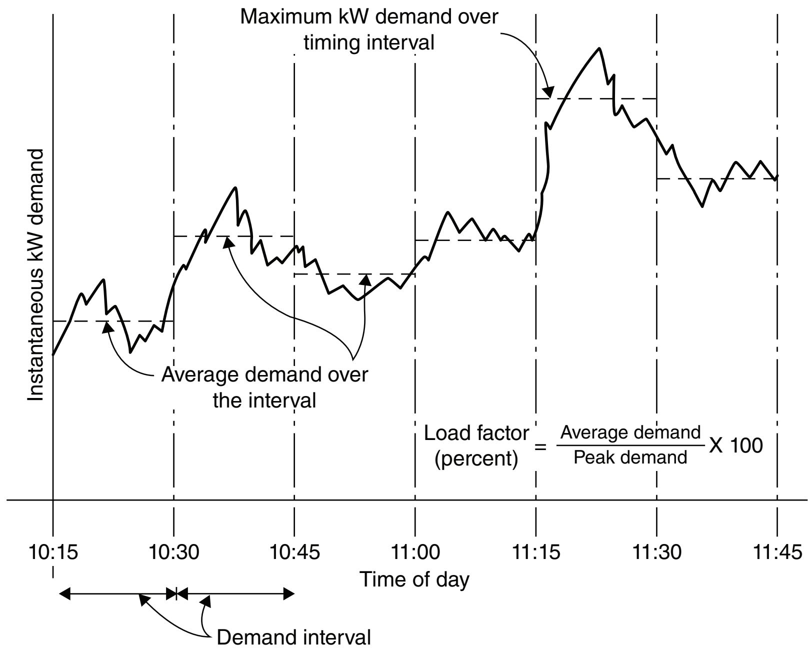


Fig. 26.13 *Typical instantaneous load curve for a commercial facility. The utility demand meter records the average demand in each period (here, 15 minutes). The maximum interval demand—in this case, between 11:15 and 11:30—is used as the basis for monthly billing. A high load factor (utilization factor) indicates that little can be gained by demand control; a low load factor indicates the reverse.*

Thus, were it not for a demand charge, the utility company, which is required by law to supply the maximum customer demand, would have to provide and maintain 100 kW of generation, transmission, and distribution facilities in return for a payment that is the equivalent of 1.11 kW of average continuous load, that is,

$$\text{equivalent continuous load} = \frac{\$80.00}{720\ \text{hr/month} \times 0.10} = 1.11\ \text{kW}$$

The user's load factor can be calculated readily. By definition,

$$\text{load factor} = \frac{\text{average power demand}}{\text{maximum power demand}} \qquad (26.8)$$

For a given time interval (e.g., day, month, year), the average power demand is equal to the energy used in the period divided by the period length.

$$\text{Average period power demand} = \frac{\text{kWh energy use}}{\text{hours of use}}\ \text{for that time period} \qquad (26.9)$$

Therefore, the average *monthly* power demand equals the average monthly energy use divided by 720 hours. Substituting the monthly version of Equation 26.9 as the general expression for the load factor (LF) in Equation 26.8 gives

$$\text{LF monthly} = \frac{\text{monthly kWh energy use} \div 720\ \text{hours}}{\text{maximum demand}} \qquad (26.10)$$

For the case under consideration, the *monthly* load factor is

$$\text{LF} = \frac{[(23\ \text{days} \times 8\ \text{h} \times 20\ \text{kW}) + (2\ \text{days} \times 4\ \text{h} \times 100\ \text{kW})] \div 720\ \text{h}}{120\ \text{kW}}$$

$$= \frac{(3680 + 800\ \text{kWh/month}) \div 720\ \text{h}}{120\ \text{kW}}$$

$$= 0.052 \text{ or } 5.2\%$$

This is a very poor load factor, which results in the levying of a high demand charge. Assuming an \$8.00 per kW demand tariff, this pottery manufacturer would be billed, monthly, an additional

$$\text{demand charge} = 120\ \text{kW} \times \$8.00 = \$960.00$$

With an energy bill of only

$$\text{energy cost} = 4480 \text{ kWh} \times \$0.10 = \$448.00$$

this manufacturer is paying heavily for high peak power use.

Although the illustration selected is somewhat extreme in its pattern of electricity use, it is not uncommon to find demand charges of the same order of magnitude as energy charges. It is impossible to eliminate demand spikes entirely, but it is certainly possible (and frequently very simple) to reduce them. Such reduction is in the interest of the user, the utility, and the public at large: the user benefits for economic reasons; the utility is able to make more efficient use of its facilities; and the general public avoids unnecessary power plant construction and associated inefficient use of fuel during partial generator loading, and benefits from overall reduction in fuel use. The last item is a secondary benefit of demand control.

The next section discusses user electric demand control, the primary function of which is to reduce electric *power* demand. This reduces demand charges and, incidentally (secondarily), somewhat reduces energy consumption. Electric demand control is different from *energy* management, which is primarily concerned with reduction of all types of energy use, including electricity. Electric demand control is frequently included as one part of an overall energy management system.

26.14 ELECTRIC DEMAND CONTROL

Electric demand control methods vary greatly in complexity and in degree of automation, but all basically perform the same task—enabling efficient utilization of available energy to produce a high load factor, resulting in a lowering of demand charges. An ancillary but important benefit is the improved utilization of building electrical power equipment, which normally runs underloaded. When demand control is incorporated during the original design (instead of as a retrofit), the result is smaller equipment, a lower first cost, and less space allocated for equipment.

For a number of years beginning in the 1980s, many utilities offered their customers rebates that covered up to 40% of the cost of equipment and renovations that would reduce maximum demand *and* overall energy use. These programs acted as a clear financial incentive for the development of cost-effective demand control and energy conservation equipment and techniques that have since become widely adopted. The result has been a considerable reduction in nationwide per capita electric power and energy use. These rebate programs reduced the investment payback period to such an extent that many (perhaps most) large power users invested large sums in electric demand control and energy conservation and management equipment.

The advantage to the energy user is obvious: lower electric bills. The advantage to the utility is equally simple. It costs $3000 to $7000 per kilowatt of generating capacity for new power plant construction (depending upon the location and required auxiliary construction), whereas rebates run from $150 to $1000 per kW conserved, with the larger amounts paid for by peak demand reduction. Because a utility must supply all the power demanded by customers, it is very much in the interest of any utility that is generating power output near the maximum capacity of its equipment to reduce loads in general and peak loads in particular.

The oldest and simplest utility-sponsored demand control scheme, still in use today, is the time-of-day-dependent, variable utility rate schedule. This scheme encourages off-peak use of electricity by offering a lower energy rate for consumption during off-peak hours. Utilities offering off-peak rates generally install, at no charge to the user, a separate time-controlled circuit switch for use with time-deferrable loads such as water heaters, well pumps, battery chargers, and the like. The circuit is energized only during off-peak hours, which typically are mid-afternoon and after midnight. One such arrangement is shown in Fig. 26.14. Note that the switch itself has no programming buttons. All programming is done by the utility with an auxiliary programmer (shown) that can be used to program many user switches.

The basic technique of *user* demand control is simple; electric loads are disconnected and reconnected in such a fashion that demand peaks are leveled off and the load factor is thereby improved. The extent to which a user's electric loads can tolerate this type of switching is an indication of the potential effectiveness of a demand controller. An installation with a large *uninterruptible* load, such as from computers or other productivity-related

Fig. 26.14 *Programmable electronic time control switch designed for time-of-use (off-peak) utility rate schedules. The programming device is separate from the switch and can be used by a utility to program many customer switches. The illustrated unit is arranged for 365-day scheduling, which permits full coordination with utility schedules that vary with the seasons of the year. Typical controlled loads include water heaters, thermal storage units, water and air accumulators, and any other load that either inherently or by design can be delayed for several hours. (Courtesy of Paragon Electric Co., Inc.)*

equipment, benefits minimally from demand control. Most industrial and commercial installations, however, contain a large percentage of interruptible loads (interruptions may be very short), and demand control systems frequently accomplish a 15% to 20% reduction in electric bills with a resultant short payback period on equipment investment.

The proliferation of demand control equipment has also produced a proliferation of nomenclature, including *load shedding control*, *automated load control*, *peak demand control*, and *programmable load control*. Descriptions that include the term *energy management* refer to devices whose primary function is the control of *energy consumption* and that secondarily are equipped to provide electric demand control.

Demand control devices are intended to control *power*, which is *timed* energy use. Demand control produces energy savings as a secondary benefit. The expression *electric demand control* is used for simplicity in the following sections. Various demand control schemes are discussed in some detail to enable the reader to differentiate them by recognizing their specific characteristics. Much equipment on the market today provides additional functions not directly related to demand control. Thus, a good understanding of the essentials of demand control schemes will greatly assist the prospective user. As with other areas of design, manufacturers' literature usually comprises a lengthy list of equipment abilities, few (if any) shortcomings, and little indication of specific or comparative applicability.

(a) Level 1—Load Scheduling and Duty-Cycle Control

This level is the simplest and most direct approach, and is applicable to all types of facilities. A facility's electric loads are analyzed and scheduled to restrict demand. Accordingly, large loads can be shifted to off-peak hours and controlled to avoid coincident operation. The scheduling can take advantage of special night and weekend utility rates for loads (such as battery charging and transfer pumping) that do not require a specific time of operation. The demand control device used is essentially a programmable time switch (see Chapter 27) applied to a number of circuits or loads. It is not, strictly speaking, a demand controller, in that no real-time measurement is made of the actual continuous electric load. Instead, the control operates on a preset timed duty cycle relying entirely on a prior analysis of the building loads. Typical applications of this device are control of HVAC loads, lighting loads, and process loads in small commercial, institutional, and industrial buildings.

(b) Level 2—Demand Metering Alarm

When, in conjunction with a duty-cycle controller, some type of continuous demand metering is installed that goes into alarm mode when a predetermined demand level is exceeded, a basic load (demand) control system is established. The load analysis discussed previously is structured and used to determine load priorities, so that when a preset maximum demand load is exceeded and the alarm sounds, loads can be shed (disconnected) manually in a preestablished order of priority—and subsequently reconnected, also in order of priority. This type of control is practical only for a moderate-size installation, inasmuch as the load-switching activity is manual.

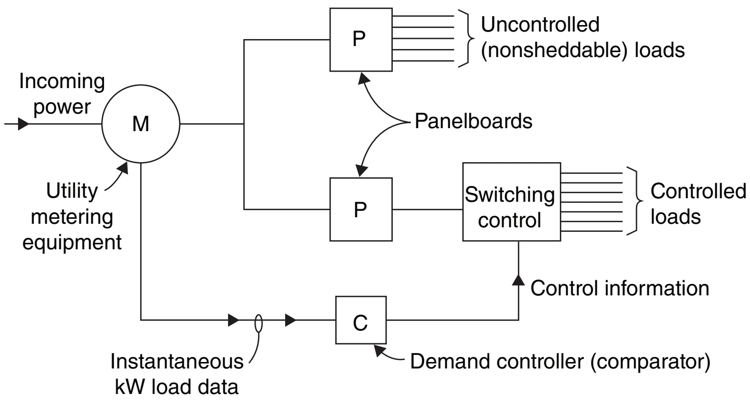


Fig. 26.15 *Block diagram of a system for automatic electric power demand control. The demand controller receives instantaneous load data from the metering equipment, compares them to preset limits, and disconnects and reconnects controllable loads automatically to keep kW demand (load) within these limits.*

(c) Level 3—Automatic Instantaneous Demand Control

This type of control (also called *rate control*) is, in effect, an automated version of the level 2 system described in the preceding section. The control unit accepts instantaneous kilowatt load information from the utility system, compares this information to a preset kilowatt limit, and acts automatically to disconnect and reconnect loads as required. These units *do not* recognize the utility's metering interval but act continuously on the basis of load comparison data. For this reason, these units are also referred to as *load comparator controllers*. Figure 26.15 will help explain the unit's operation.

Typical sheddable loads might include nonessential lighting, some cooling load, domestic hot water heating, snow melting, and the like. Nonsheddable loads (that do not tolerate even short interruption) might include essential lighting, elevators, communications equipment, computers, process control, emergency equipment, and the like. The nonsheddable loads are fed directly from the power line. The sheddable loads are fed through a panel of control relays that respond to on/off instructions from the demand controller. Although the resulting energy use with or without the controller is theoretically the same, in practice energy savings of 15% and more are common.

The principal drawback of this system is that the load shedding is preprogrammed. This results in an inability to readily adapt to varying load patterns resulting from variable production schedules, time schedules, changes in weather, and so on. As a result of this limitation, this system is most useful in applications where operating modes do not change frequently, and the facility is not very large. Thus, stores, supermarkets, warehouses, small industrial facilities, and commercial installations are well served with this type of system if they have at least 20% sheddable loads and their connected electric load is at least 150 kilovolt-amperes (kVA).

This level of demand control—as well as levels 4 and 5, described in the following sections—is most often supplied as one of many functions of a larger building energy control system. Because of this bundling, it is necessary to ascertain that the type of demand control to be supplied by the overall building control hardware and software is what the electrical system designer intended.

(d) Level 4—Ideal Curve Control

This control function operates by comparing the actual rate of *energy* usage to an ideal rate and controlling kilowatt demand by adjusting the total *energy* used within a metering interval. The utility company determines the demand over the demand interval by integrating the kilowatt-hour energy consumption over the interval and dividing by the interval time. Thus, the user is actually given a block of energy (kWh) that can be utilized at any desired rate, not necessarily at a constant rate. The desirable rate of energy use is shown as the "ideal curve" on the typical usage curve shown in Fig. 26.16.

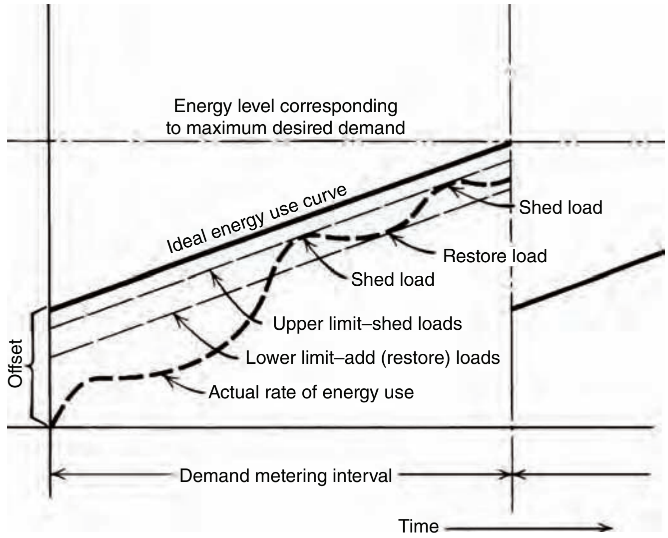


Fig. 26.16 *Graph of the action of an ideal rate controller. Note that toward the latter part of the period the pattern has been established, and the actual rate of energy use corresponds closely to the ideal. This type of control is often simply a part of the software in a large, centralized building control system.*

Shed points can be programmed independently for each load according to a predetermined priority, and priorities can be readily adjusted and rescheduled. Loads are normally shed only toward the end of an interval—when the permissible energy total for the interval is approached—and all loads are restored at the beginning of the next interval. Thus, during each interval, sheddable loads are off for only a few minutes at most. Controllers operating on the ideal curve principle are considerably more flexible than the kilowatt rate controller described in the level 3 system, and are applicable to facilities of widely divergent load size, but with at least a 300-kW connected load. As with other controllers, the principal savings will be in demand charges, but almost always with considerable savings in energy billings.

(e) Level 5—Forecasting Systems

These systems are by far the most sophisticated, the most expensive, and the most effective. They are best applied to large facilities where the number of loads, load patterns, and complexity of operation preclude the effective use of the preceding systems. Because of the large amount of load data that needs to be processed, these systems are usually installed as part of a computerized central control system. Details of operation are too complex to be described here, but the basic operation can be outlined. These control units operate by continuously forecasting the amount of "unpenalized" energy remaining in the demand interval, based upon kilowatt-hour data received. They then examine the status and priority of each of the connected loads and decide on a course of action. Loads that in other systems are classified as nonsheddable are, in this system, controlled because of the accuracy and rapidity of the control function. A pneumatic compressor, for instance, that supplies process air might, in lower-level control systems, be classified as noncontrollable, despite the fact that it has long off periods. With computer control, such a load would be classified as "delayable" or "inhibited" because a 30-second or 1-minute delay in activation after the pressure switch closes its contact is normally acceptable.

The advantage of these systems is that, if programmed properly, they can make small, accurate load changes throughout an interval, resulting in minimum load cycling and maximum efficiency.

26.15 ELECTRICAL MEASUREMENTS

The preceding sections have explained the fundamental electric quantities of voltage and current and defined the units involved as volts and amperes,

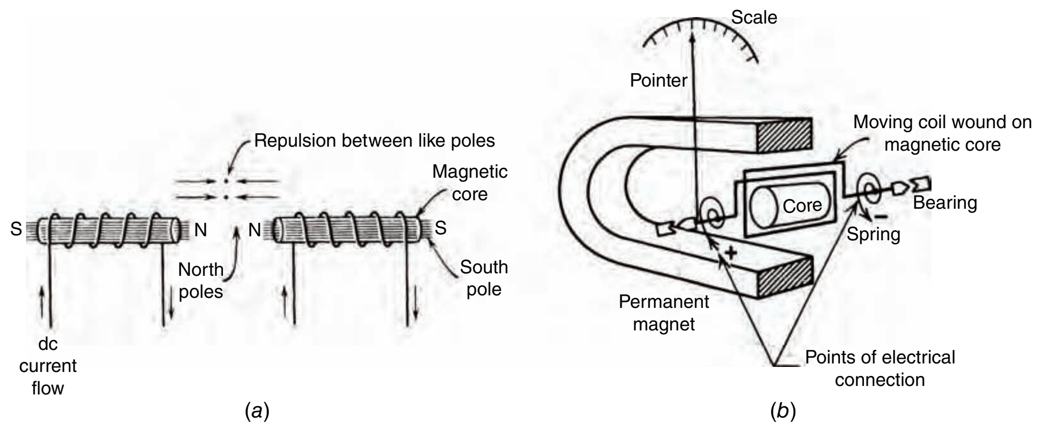


Fig. 26.17 *(a) Diagram showing the basic electromagnetic principle and interaction between electromagnets. Any iron core becomes an electromagnet when current flows in a coil wound around it, as shown. (b) The principle of the electromagnet is used in this basic meter movement. Current flowing in the movable coil forms an electromagnet whose field interacts (see a) with the permanent magnet's field, causing a deflection proportional to the current flow. (Courtesy of Wechsler, a division of Hughes Corp.)*

respectively. As is true of all physical quantities used in practical applications, a need exists for a simple means of measuring these quantities. This need was initially met by the development of the meter movement, illustrated in Fig. 26.17.

Everyone at one time or another has felt the repulsion between like poles of two magnets held close together and, conversely, the attraction between opposite poles. This principle was used in the first basic meter movement: causing a deflection of the pointer as a result of the repulsion between the field of a permanent magnet and an electromagnet. The electromagnet is formed when current flows in the coil, and its strength is proportional to the amount of current. Thus, a strong current causes a larger deflection of the needle and therefore a higher reading on the dial. A spring (see Fig. 26.17*b*) provides restraining torque on the pointer. To make this very sensitive unit usable for large currents (it is intrinsically a micro-ammeter, sensitive to millionths of an ampere), the device simply diverts, or *shunts* away, most of the current, allowing only a few microamperes to actually flow in the meter coil.

To use the same device as a voltmeter, a large resistance called a *multiplier* is placed in series with the meter, thereby again limiting the current flow to a few microamperes. The meter scale is then calibrated in volts. All DC meters are made in this fashion. Most AC meters operate on basically the same principle, except that instead of a permanent magnet, an electromagnet is used. Thus, when the polarity reverses, the deflecting force retains the same direction. A DC meter connected to an AC circuit simply will not read because inertia prevents the needle from bouncing up and down 60 times a second.

The meters just described are conventional analog devices that read electrical values in proportion to mechanical forces exerted within the device—that is, by analogy. Modern electronics has produced a line of solid-state electrical meters (Fig. 26.18) that display the measured electrical values in analog mode (needle on a dial), digital mode, or both. They operate in a number of ways, all of which are different from that described previously and are beyond the scope of this book.

The fact that a meter reads digitally does not necessarily mean that it is highly accurate. Accuracy depends upon the quality of the internal circuitry. Digital meters are easier to read than analog meters because no visual interpretation or interpolation is involved. This advantage, plus the constantly declining cost of sophisticated electronics, will undoubtedly lead to solid-state digital meters replacing analog types, except for special applications.

(*a*) (*b*)

Fig. 26.18 *(a) Solid-state clamp-on type meter with digital readout and automatic ranging. The latter feature eliminates the necessity to preselect a meter range and is particularly useful where the magnitude of current or voltage is unknown. The clamp-on feature permits use without wiring into, or otherwise disturbing, the circuit being measured. The meter measures approximately 8 × 3 × 1.5 in. (200 × 75 × 40 mm), weighs less than 1 lb (0.5 kg), and is battery-powered. Scales are 0.1–1000 amp AC, 0.1–1000 V AC, and 0.1–1000 ohms resistance, with ±2% accuracy. (b) Solid-state auto-ranging clamp-on AC meter with analog-type readout. It is similar in design to the meter in (a), but with somewhat larger range scales and additional features such as peak current measurement. (Photos courtesy of TIF Instruments, Inc.)*

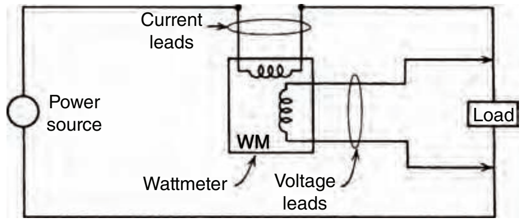


Fig. 26.19 *Schematic arrangement of wattmeter connections. Note that the current coil is in series with the circuit load, whereas the voltage leads are in parallel.*

In buildings, the measurement of current and voltage is generally not as important as the measurement of power and energy. To measure power, the fact that power is proportional to the product of the voltage and current in a circuit is employed. Although actual construction is complex, the theory of operation of a conventional coil-type wattmeter is simple. The meter has two coils: a current coil that is similar in connection to an ammeter and a voltage coil that is similar in connection to a voltmeter (Fig. 26.19). By means of the physical coil arrangement, the meter deflection is proportional to the product of the two and therefore to the circuit power. The meter can be calibrated as desired, depending upon the size of the shunts and multipliers.

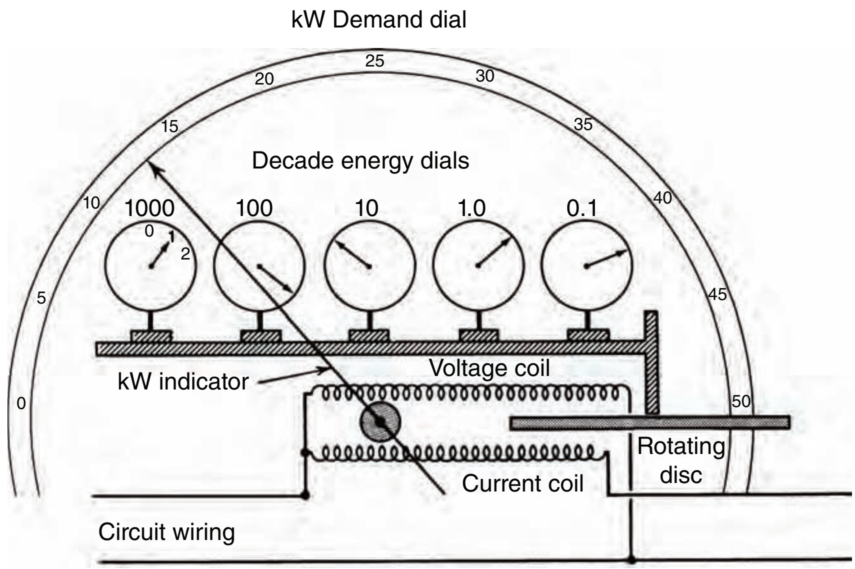
To measure energy, the factor of time must be introduced because

$$\text{energy} = \text{power} \times \text{time}$$

Direct-current energy meters are available but are not of general interest because of the rarity of DC power. Alternating-current watt-hour meters are basically small motors, whose speed is proportional to the power being used. The number of rotations is counted on the dials, which are calibrated directly in kilowatt-hours. A diagram of the basic construction of an AC kilowatt-hour meter is shown in Fig. 26.20. As can be seen, kilowatt-hour energy consumption and maximum interval kilowatt demand can be read directly from the dials. If the numbers involved are too large (because of calibration), a multiplying factor is required to arrive at the proper kilowatt-hour consumption. This number is written directly on the meter nameplate, and the meter reading is multiplied by it to get the actual kilowatt-hours. Several other types of multifunction and energy meters are shown in Figs. 26.21, 26.22, and 26.23.

Continuous monitoring of the electrical characteristics of an entire distribution system, or of a portion fed from a specific switchboard, can be readily accomplished by use of solid-state devices. Such programmable system analyzers can be arranged to measure power usage, perform power quality and harmonic analyses (and the like), and display the results locally and/or remotely.

A number of interesting, labor-saving kilowatt-hour meters have been developed to make electricity billing and control easier. One type is equipped with a programmable electro-optical automatic meter-reading system that can be activated locally or from a remote location. The meter data are transmitted electrically to a data-processing center, where they may be used by the utility to prepare subscribers' bills; prepare customer load profiles; and study, in combination with other data,



Interactive Animation

Fig. 26.20 *Typical induction-type kilowatt-hour meter with kilowatt demand dial. Dials register total disc revolutions, which are proportional to energy. Disc rotational speed is proportional to power. Note that the current coil is in series with the load and that the voltage coil is in parallel.*

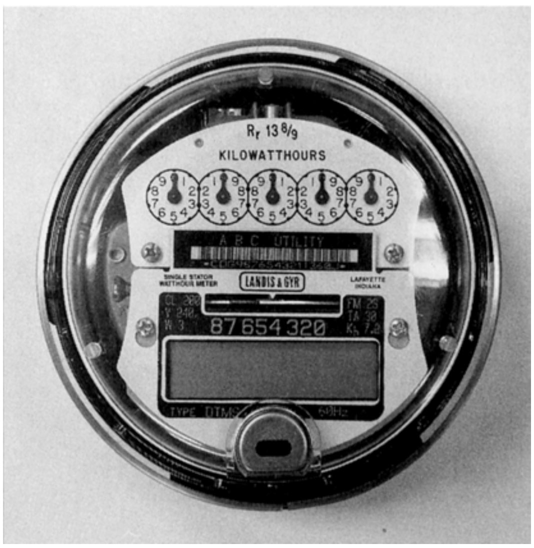


Fig. 26.21 *A multifunction solid-state kWh meter. This single-phase meter includes a mechanical register similar to that shown in Fig. 26.20 plus a large liquid crystal display. It can be arranged to provide either time-of-use billing or demand/time-of-use billing in addition to its energy measurement function. It can also be configured to provide load control, demand threshold alert, end-of-interval alert, and load profile recording. (Photo courtesy of Landis and Gyr.)*

Fig. 26.22 *A digital kWh meter. Some digital meters allow homeowners to track their energy consumption in one-hour increments online. (Photo courtesy of Landis+Gyr.)*

Fig. 26.23 Handheld clamp-on ammeter. This ammeter has a maximum jaw width of 1.18 inches (30 mm) and is capable of measuring up to 400 amps of alternating current.

area load patterns, equipment loadings, and so on. The customer can use instantaneous data to control loads, as explained in the preceding section.

Another meter type is equipped with a miniature radio transmitter that can be remotely activated to transmit the current kilowatt-hour reading. The meter reader moves along a street and remotely activates a meter by entering a customer code into a digital pad. A special receiver not only receives the transmitted kilowatt-hour data but encodes and records the data automatically. These and other "smart" kilowatt-hour meters are more costly than traditional meters, but they are gradually being introduced because of large reductions in labor costs and increases in the quantity and quality of data made available. In this regard, programmable meters are currently being deployed among residential customers in some areas to allow utility company control of demand (with the agreement of the consumer—usually resulting from a more favorable rate structure). Air-conditioning load-shedding controls are fairly common in many parts of the United States.

C H A P T E R 27

Electrical Systems and Materials: Service and Utilization

THE FIRST STEP IN DEVELOPING AN UNDERSTANDING OF building electrical systems is to examine the means by which electric service is brought into a facility.

27.1 ELECTRIC SERVICE

The codes and standards that apply to electric service include:

1. *National Electrical Code* © National Fire Protection Association; in particular, Section 230.
2. *National Electrical Safety Code*, published by the Institute of Electrical and Electronics Engineers (IEEE; www.ieee.org). This code is recognized by the American National Standards Institute (ANSI). It deals with clearances for overhead lines, grounding methods, underground construction, and related matters.
3. Standards of the utility supplying electric service.

Public utility franchises in the United States require only that service be made available at the private property line. Thus, service is normally connected to the utility lines at a mutually agreeable point at or beyond the property line. The service tap may be a connection on a pole with an *overhead service drop* or an *underground service lateral* to the building, or a connection to an underground utility line with a service lateral to the building. Electrical construction work on private property is usually at the owner's expense.

Under certain conditions, the owner can influence the type of service connection utilized by the electric utility company in conveying electric service to a site. This is often the case in large tract developments and in places where owners are willing to share some of the cost of better-grade construction. Also, in many areas, the utilities themselves have instituted "beautification" programs in an effort to decrease the objectionable appearance of much of their equipment.

Service from a utility line to a building may be run overhead or underground, depending upon the following factors:

- Length of the service run
- Type of terrain
- Customer participation in the cost of service installation
- Service voltage
- Size and nature of the electric load
- Importance of appearance
- Local practices and ordinances
- Maintenance and service reliability
- Weather conditions
- Type of interbuilding distribution, if applicable

27.2 OVERHEAD SERVICE

The principal advantage (to the utility) of overhead electric lines is low cost. Depending upon terrain and other factors, the cost saving of overhead compared to underground installation has historically ranged from 10% to 50% (the latter when compared to direct burial cable installation). This accounts for the majority of installations being overhead. In recent years, special techniques in underground installation have lowered that cost, making it a reasonable economic alternative when its advantages are considered.

Where the length of the service run is several hundred feet (meters) or more, voltages higher than the facility's utilization level may be involved. This heavily favors installation of overhead lines, particularly with voltages exceeding 5000 V. Similarly, when terrain is rocky and the electrical load is heavy, the cost of underground installation is prohibitive. Because overhead lines are easily maintained and repaired and faults easily located, service continuity with overhead lines is generally acceptable. In areas with severe weather conditions, called *heavy loading areas*, where combinations of snow, wind, and ice increase the possibility of outages on overhead lines, underground service is preferable. This is particularly true when even short service outages cause hardship or financial loss. Reliability of overhead service can be improved markedly by taking service from two separate, and preferably separated, overhead lines. A final decision on the type and location of electrical service will be made after meetings among the building's architect, the electrical engineer, and the electric utility's technical personnel.

Overhead cables are of several types: bare, weatherproof, or preassembled aerial cable. Bare copper cables supported on porcelain or glass insulators on crossarms are normally used for high-voltage lines (2.4 kV and higher). Low-voltage circuits (600 V and below) are generally run on porcelain spool secondary racks using single-conductor (1/c) weatherproof cable. Preassembled aerial cable consists of three or four insulated cables wrapped together with a metallic tape and suspended by hooks from poles. This type of construction may be used for voltages of up to 15 kV (Fig. 27.1), and often proves to be more economical than crossarm or rack installation and more resistant to damage from severe weather conditions.

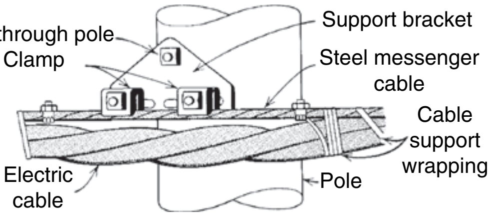


Fig. 27.1 *Preassembled aerial messenger cables are carried by steel cables clamped to poles.*

A typical detail of an overhead electric service entrance to a multiresidence building is shown in Fig. 27.2.

27.3 UNDERGROUND SERVICE

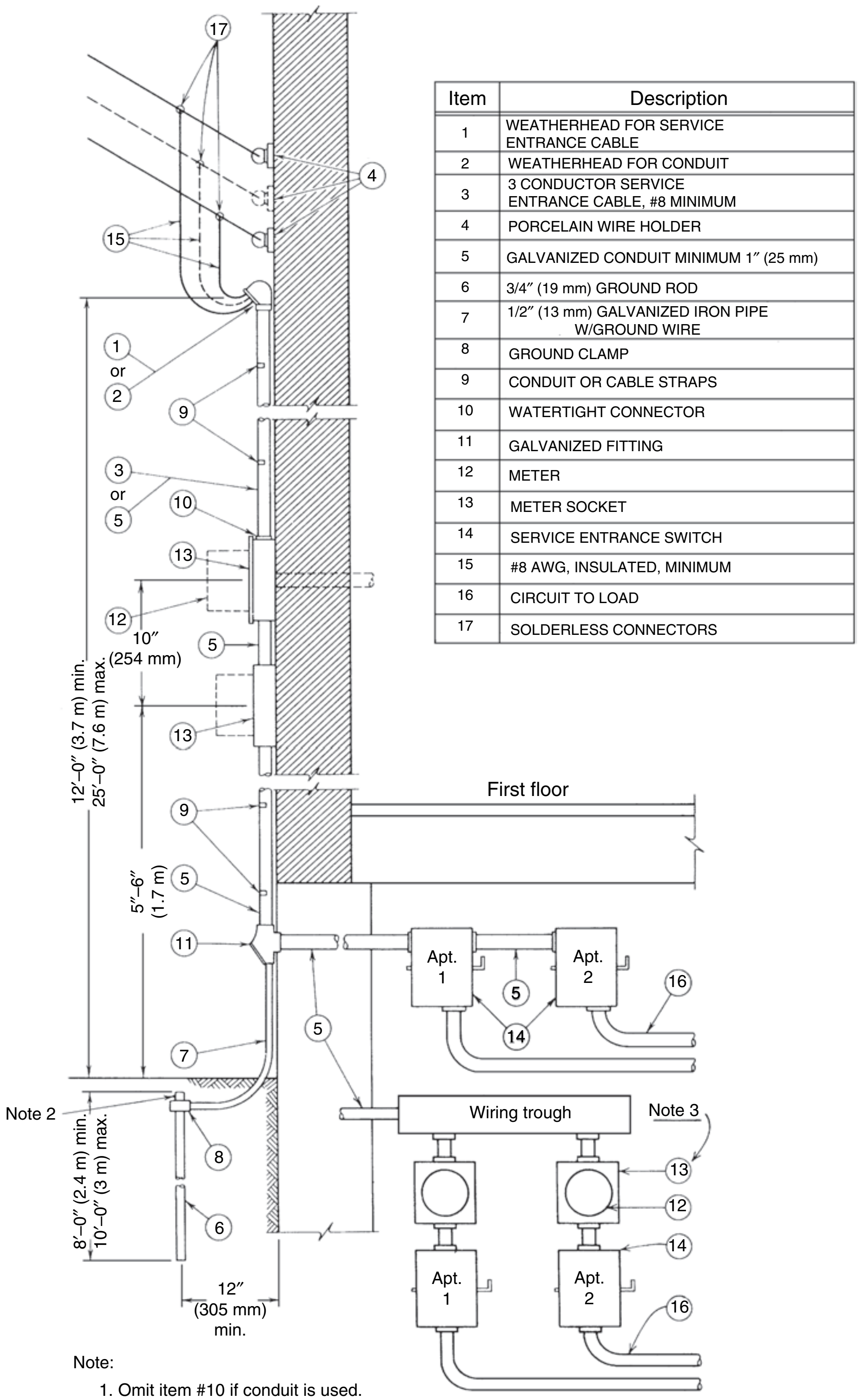
The advantages of underground electric service are attractiveness (lack of physical and visual clutter overhead), service reliability, and long life. The principal disadvantage is high cost. To overcome this, utilities frequently use direct burial techniques that, by eliminating a raceway, reduce costs considerably. Because direct buried cable cannot be pulled out if it faults, as is the case with raceway-installed cable, restoration of service after a cable fault is time-consuming. It is recommended that the decision on which technique will be used be based upon consideration of these factors:

- The cost premium for underground raceway installation, including handholes if required (see Section 27.4)
- The history of outages for direct burial installation by this installer, in the immediate area
- Cost and availability of repair service (utilities frequently will repair customer-owned underground service laterals for a fee)
- Impact of electric service outage in terms of time delays, inconvenience, necessity of digging up lawns and paved areas, and cost impact in the case of a commercial facility

27.4 UNDERGROUND WIRING

The methods available for underground wiring are:

- Direct burial (Fig. 27.3)
- Installation in Type I, concrete-encased duct (Fig. 27.4*a*)
- Installation in Type II, direct burial duct (Fig. 27.4*b*).



Item	Description
1	WEATHERHEAD FOR SERVICE ENTRANCE CABLE
2	WEATHERHEAD FOR CONDUIT
3	3 CONDUCTOR SERVICE ENTRANCE CABLE, #8 MINIMUM
4	PORCELAIN WIRE HOLDER
5	GALVANIZED CONDUIT MINIMUM 1″ (25 mm)
6	3/4″ (19 mm) GROUND ROD
7	1/2″ (13 mm) GALVANIZED IRON PIPE W/GROUND WIRE
8	GROUND CLAMP
9	CONDUIT OR CABLE STRAPS
10	WATERTIGHT CONNECTOR
11	GALVANIZED FITTING
12	METER
13	METER SOCKET
14	SERVICE ENTRANCE SWITCH
15	#8 AWG, INSULATED, MINIMUM
16	CIRCUIT TO LOAD
17	SOLDERLESS CONNECTORS

Note:

1. Omit item #10 if conduit is used.
2. Cold water pipe ground may be used in lieu of ground rod.
3. Meters may alternatively be placed inside the building.

Fig. 27.2 *Detail of typical overhead electric service to a four-family residence. Note that meters in small residential buildings are frequently placed on the exterior of the building. Alternatively, they can be installed inside, provided that ready access is available or some type of remote meter-reading system is installed.*

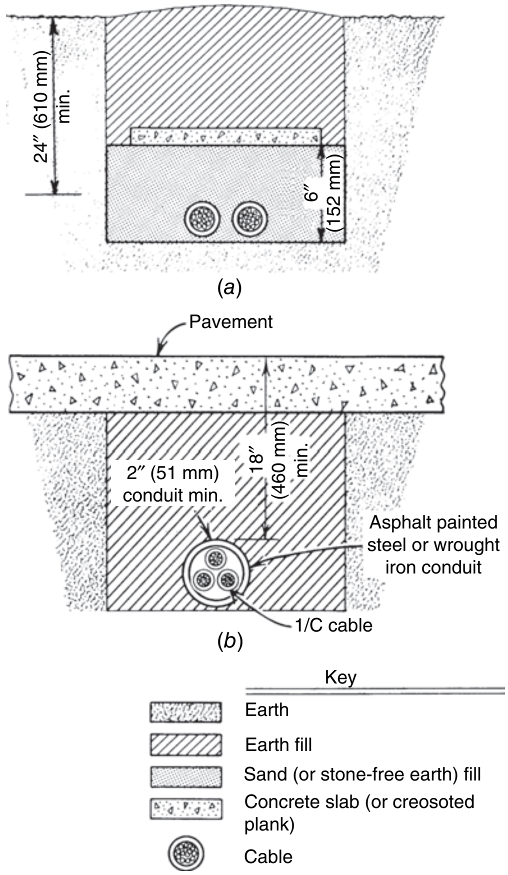


Fig. 27.3 *(a) Technique for installation of direct-burial cable. (b) Under highways, streets, and other high-load areas, cable should be installed in metal conduit.*

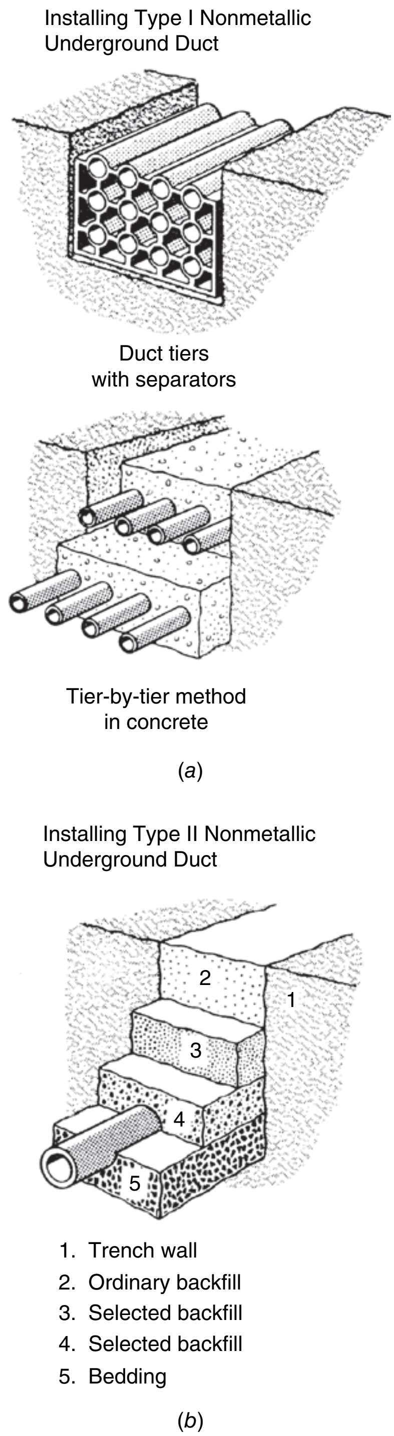


Fig. 27.4 *Underground duct installation. (a) The concrete duct bank should have at least 6 in. (150 mm) of earth cover. (b) Heavy-wall duct should be buried at least 24 in. (600 mm) in ordinary traffic areas and 36 in. (900 mm) in areas subject to heavy traffic. Each layer is about 8 in. (200 mm) thick.*

The first alternative offers low cost and ease of installation, with the disadvantage regarding repairs stated previously. The second offers high strength and permanence, but at the highest price of the three. The last offers median cost but little strength. It is applicable only for installations on undisturbed earth and/or under light paving.

Nonmetallic duct (conduit) intended for underground electrical use is commercially available in two wall thicknesses. NEMA (National Electrical Manufacturers Association) Type II with a heavy wall provides the physical protection required for direct burial installation with no concrete encasement. Type I is manufactured with a thinner wall and is intended for encasement in a minimum of 2 in. (50 mm) of concrete. Such ducts may be manufactured from a variety of materials and are sold under several trade names. Plastic conduit is referred to as *PVC* or simply as *plastic*.

Nonmetallic conduit is most frequently used without concrete encasement for low-voltage and signal wiring and with encasement for high-voltage wiring. It offers several advantages over steel conduit for underground work, such as lower cost and freedom from corrosion.

When underground electric wiring is duct-installed and the run extends over several hundred feet (meters)—the exact distance depending upon the pulling tension; a pulling handhole or manhole is necessary. Handholes are used for low-voltage power and signal cables and for runs with a small number of cables. Manholes are used for high-voltage cables and where large duct banks must be accommodated. Precast handholes and manholes are readily available in many standard sizes and are usually cheaper than field-formed and poured units.

Cable used in underground wiring must be specially manufactured and approved for that purpose. Type SE is the basic service entrance cable, constructed with a moisture- and flame-resistant covering. When it is provided with moistureproofing for underground use, the designation is SE type U, or simply USE. Underground cable for other than service runs is classified as type UF (underground feeder).

27.5 SERVICE EQUIPMENT

Referring to Fig. 28.1, note that a block labeled "transformer" is located between the high-voltage incoming utility lines and the secondary service conductors. This equipment item is required whenever the building utilization voltage is different from the service voltage. A transformer may be pole- or pad-mounted outside the building or installed in a room or vault inside the building, as discussed later.

27.6 TRANSFORMERS

A transformer is a device that changes or *transforms* alternating current (AC) of one voltage to alternating current of another voltage. Transformers used in building work consist essentially of an iron core on which are wound at least two coils: a primary (coil) winding and a secondary (coil) winding. A voltage impressed on the primary winding induces (through the iron core) a voltage in the secondary winding in proportion to the ratio of turns in the two coils. Thus, a *step-down* transformer has a larger number of turns in its primary winding than in its secondary winding, and a *step-up* transformer has the reverse. In theory, transformers are reversible, although in practice they are rarely used that way. Transformers cannot be used on DC.

A transformer typically is used to step down an incoming 4160-V service to 480-V for distribution within a building. Another transformer is then used to step down the 480 V to 120 V for use with receptacle circuits. Ordinarily, 120, 208, 240, 277, and 480 V are called *low* or *secondary voltages*, and 2400, 4160, 7200, 12,470, and 13,200 V are *high* or *primary voltages*.

Transformers are available in single-phase or three-phase construction. Transformer power capacity is rated in kilovolt-amperes (kVA). For a single-phase unit, this figure is the product of the full load current and the voltage. Because the voltages on the primary and secondary are different, so are the primary and secondary currents—because the kVA remains constant.

For example, a single-phase 100-kVA, 2400/120-V transformer will carry at full load:

$$\text{primary current} = \frac{100{,}000\ \text{VA}}{2400\ \text{V}} = 41.6\ \text{A}$$

$$\text{secondary current} = \frac{100{,}000\ \text{VA}}{120\ \text{V}} = 832\ \text{A}$$

That is, the ratio of primary to secondary current is exactly the reverse of the ratio of primary to secondary voltage, because their product, which is the transformer's kVA rating, remains constant. Expressed in an equation,

$$\text{primary current} \times \text{primary voltage} = \text{secondary current} \times \text{secondary voltage}$$

or

$$V_p I_p = V_S I_S \tag{27.1}$$

where
V_p is the primary voltage
I_p is the primary current
V_S is the secondary voltage
I_S is the secondary current

Heat is generated by the passage of current through the transformer coils due to the winding cable resistance. This heat is transferred to the unit's *cooling medium*, where it is radiated or otherwise disposed of. The unit's cooling medium is a property of major importance. Transformers are either dry (air-cooled) or liquid-filled. The choice depends upon the required electrical characteristics, the proposed physical location of the transformer, and costs. Although detailed considerations are beyond the scope of this book, some selection criteria are presented in the following sections. In general, units rated above 5 kV are liquid-filled, and units in the 600-V class are dry. Units installed indoors, except in vaults, are normally of the dry type, and are intended for general-purpose lighting and power circuits (Table 27.1). *Load center* transformers are installed in unit substations, both indoor and outdoor. *Distribution* transformers are mounted on a pole or on a concrete pad outdoors. *Substation* transformers are large and are always mounted on a concrete pad.

The *insulation class* of a transformer affects its permissible temperature rise and operating temperature, and, as a direct result, its physical size, electrical power losses, overload capacity, and life.

The physical size of a transformer of a given kVA rating and voltage depends upon the type of insulation used. In order of decreasing physical size and increasing operating temperature, we have, for dry transformers, 105, 150, 185, and 220°C (221, 302, 365, and 428°F) systems that represent organic, inorganic (two types), and silicone insulating materials, respectively (Table 27.2).

Dimensional data for transformers vary considerably from one manufacturer to another. Therefore, Table 27.3 is useful only to provide a sense of bulk volume and weight.

Although 220°C (428°F) system insulation transformers can withstand a 150°C (270°F) rise (see Table 27.2), some users specify 220°C (428°F) system insulation with a 115°C (207°F) rise or even an 80°C (144°F) rise; that is, a better grade of insulation is used with an *underrated* transformer. There are four advantages to this design decision:

- Longer life
- Higher overload capacity
- Lower operating cost
- Increased capability to withstand the heating effects of harmonics commonly found in commercial and industrial electrical systems (see Section 29.18)

A 220°C (428°F) system transformer operated at full load *continuously* (an unusual situation) has a short life—estimated on the basis of accelerated aging tests to be between 3 and 10 years. The same class insulation transformer (220°C [428°F] system) rated at 80°C (144°F) has a life expectancy of more than 100 years. With respect to operating cost, the same issues apply here as with the selection of high-temperature insulation discussed in Section 28.8 and summarized in Table 27.2. The adage that you get what you pay for can be expressed here as follows: In return for a smaller, lighter, cheaper, and hotter transformer (220°C [428°F] system), there will be higher losses, and therefore a higher operating cost and a shorter life.

TABLE 27.1 Typical Transformer Data

Transformer Type (Application)	Maximum Capacity[a] (kVA)	Insulating (Cooling) Medium	Voltage Range: Primary	Voltage Range: Secondary
General-purpose, dry type	1000	Air	120–600 V	120–600 V
Load center pad-mounted unit substation	3000	Air	2.5–15 kV	120–600 V
Load center pad-mounted unit substation	5000	Oil	2.5–34.5 kV	120–4800 V
		Silicone fluid[b]		
		Epoxy/resin[c]		
Distribution system	10,000	Oil	2.5–67 kV	120–4800 V
		Silicone		

[a]Three-phase bank.

[b]High-fire-point paraffinic hydrocarbon fluid, manufactured expressly as a transformer dielectric-coolant.

[c]Solid dielectrics used for special installation, such as in high-hazard areas.

TABLE 27.2 Air-Cooled Transformer Electrical Insulation Temperature Ratings (Based on 40°C Ambient)

Insulation Class System[a]	Insulation Type	Average Conductor Temperature Rise	Ambient Temperature	Hot-Spot Temperature Gradient	Total Maximum Temperature
105°C	Organic (A)	55°C	40°C	10°C	105°C
150°C	Mica, glass, resins (B)	80°C	40°C	30°C	150°C
185°C	Asbestos (F)	115°C	40°C	30°C	185°C
220°C	Silicones (H)	150°C	40°C	30°C	220°C

[a]Modern terminology for insulation class uses *system* in lieu of *class*.

Note: Ratings are expressed in °C. Equivalent I-P values are: (a) for temperatures—40 (104 °F) 105 (221), 150 (302), 185 (365), 220 (428); (b) for temperature increments—10 (18 F°), 30 (54), 55 (99), 80 (144), 115 (207), 150 (270).

It is good practice in buildings with a total transformer capacity in excess of 300 kVA to complete a calculation comparing the operating costs of various types of transformers in order to balance energy costs with necessary operating flexibility, reliability, and safety.

Such a calculation (using generic cost data) was performed assuming a daily/weekly operating cycle and loading that is representative of commercial use. The two transformers studied were of the dry type, rated 750 kVA, one designed for an 80C° (144F°) rise and the second for a 150C° (270F°) temperature rise. At an energy cost of 7 cents per kWh, the lower energy waste of the more expensive 80C° (144F°) unit repays the first-cost differential in about 4 years. A higher electric energy cost reduces the payback time, and vice versa. Beyond the payback period, the advantage is entirely on the side of the 80C° (144F°) unit. Using a 30-year life, 8% fixed capital cost, and 3% annual cost escalation, the life-cycle cost of the 80C° (144F°) unit is US$10,000 less than that of the 150C° (270F°) unit. (At the assumed loading, even the 150C° [270F°] unit will probably last 30 years, the 80C° [144F°] unit much longer.)

Furthermore, with a total permissible hot-spot temperature of 220°C (428°F), the location of the 150C°-rise (270F°-rise) unit must be very carefully chosen because it can create a serious heat generation and radiation problem.

To summarize, a transformer is specified by type, phase, voltages, kVA rating, sound power level, and insulation class. Thus, a 112.5-kVA, three-phase, 480/120–208-V, air-cooled, indoor, dry-type transformer with a 220°C (428°F) insulation

TABLE 27.3 Typical Dry-Type Transformer: Dimensions and Weights[a]

kVA Output Continuous	Temp Rise (C°)	Approximate Dimensions in. (mm) H × W × D	Approx Weight lb (kg)
		PRIMARY: 480 V SECONDARY: 120/240 V	
		Single-phase	
3	115	13 × 8 × 8 (330 × 203 × 203)	60 (27)
5	115	14 × 12 × 12 (356 × 305 × 305)	120 (54)
10	115	15 × 12 × 12 (381 × 305 × 305)	150 (68)
15	150	24 × 16 × 16 (610 × 406 × 406)	200 (91)
25	150	24 × 16 × 16 (610 × 406 × 406)	230 (104)
50	150	30 × 20 × 20 (762 × 508 × 508)	430 (195)
100	150	40 × 24 × 24 (1016 × 610 × 610)	650 (295)
		PRIMARY: 480 V SECONDARY: 208Y/120 V	
		Three-phase	
45	150	26 × 26 × 15 (660 × 660 × 381)	380 (172)
75	150	30 × 30 × 20 (762 × 762 × 508)	600 (272)
150	150	40 × 36 × 26 (1016 × 914 × 660)	1100 (499)
225	150	44 × 36 × 26 (1118 × 914 × 660)	1400 (635)

[a]Dimensions and weights vary among manufacturers. All figures increase with higher primary voltage and with lower temperature rise.

Note: 115 C° rise = 207 F°; 150 C° = 270 F°.

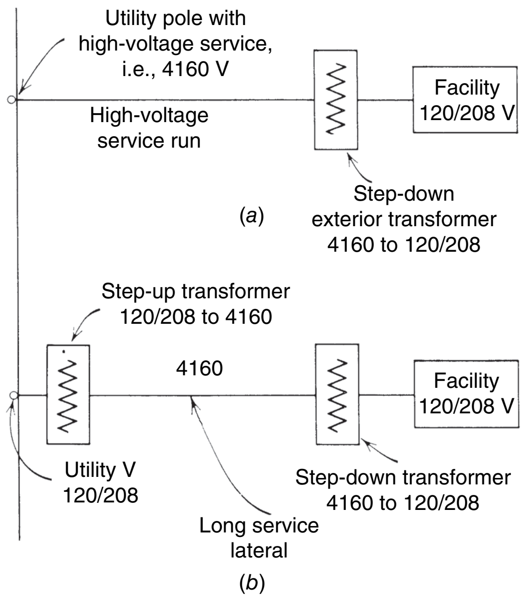


Fig. 27.5 *Service transformer arrangements. (a) High-voltage service with a step-down service transformer at the facility and (b) low-voltage service, with transformers at both ends of a long service run.*

system and 115C° (207F°) rise, and a 45-dBA (decibel) maximum sound power level, represents an adequate transformer description. Sound ratings of transformers, as well as installation techniques and acoustical treatment, are discussed in Part V.

A service transformer bank is necessary when the facility utilization voltage is different from the utility voltage (Fig. 27.5*a*). A building design may call for a step-up, step-down arrangement when the service run is so long that the conductor cost, when run at a low voltage, would be excessive because of large cables. In such instances, the cost of the double transformer installation must be more than offset by the savings in feeder cost, to be economically justifiable (Fig. 27.5*b*). More commonly, step-down transformers are the norm.

27.7 TRANSFORMERS OUTDOORS

The advantages of an outdoor transformer installation are:

- No enclosed building space is required
- Reduced probability of a noise problem within the building
- Lower first cost
- Ease of maintenance and replacement
- No interior heat production
- Opportunity to use low-cost, long-life, oil-filled units

Although an exterior installation comes with pluses, it is frequently easier to find space indoors (preferably in a basement) than to find a holistically suitable exterior location. Noise may be more disturbing in the context of some available exterior spaces, such as courtyards, than with a basement location. Costs can be high if long secondary voltage runs are required; heat can often be handled by louvers or areaways adjoining a basement, or even used beneficially if the transformer load is fairly constant. Because exposure to direct solar radiation decreases a transformer's rating by increasing its temperature, a shaded exterior location is preferable, but may be difficult to find. Furthermore, an exterior transformer, other than pole-mounted, is a questionable choice in an area with a high incidence of vandalism, regardless of the sturdiness of construction.

Finally, the appearance of an exterior unit may be objectionable. This point has received much attention from manufacturers, and numerous designs have been developed that minimize aesthetic concerns (Fig. 27.6). The most popular type of exterior transformer installation is the pad mount. It has all of the advantages listed previously in addition to extreme simplicity of installation—it is set on a simple concrete pad. Consult manufacturers' catalogs for dimensional data.

27.8 TRANSFORMERS INDOORS: HEAT LOSS

When an indoor transformer installation is indicated, special consideration must be given to the transformer's heat-generating properties. Between 1% and 1½% of a transformer's load rating, depending upon the type, is converted to heat at full load. For a 750-kVA, dry-type, 150C°-rise (270F°-rise) unit, 12 kW, or 41,000 Btu/h, of heat loss is generated at full load! Losses are lower for 80C°-rise (144F°-rise) units. Liquid-filled units have approximately the same losses as 80C°-rise (144F°-rise) dry units. Unless the heat can be used, sufficient ventilation—either natural or forced—must usually be provided to keep the transformer room's ambient temperature from exceeding 40°C (104°F).

(a)

(b)

Fig. 27.6 (a) Pad-mounted exterior transformers are neat, compact, and, if sited properly, unobtrusive. Large units can be partially screened by shrubbery. (b) When the size is such that visual screening becomes a problem, consideration should be given to a structural screen such as a decorative brick wall. (Courtesy of General Electric, USA.)

Ventilation by natural convection is most desirable, requiring the transformer room be located on an exterior wall (adjacent to an areaway if the room is located below grade). The required size (the *free* area) for a ventilation opening is 3 in.^{2}/kVA (1935 mm^2/kVA) of capacity, plus an additional 1 in.^{2}/kVA (645 mm^2/kVA) for switchgear heat losses, if any. If a louver is used to protect the ventilation opening, the size of the opening must usually be doubled (total: 8 in.^{2}/kVA [5160 mm^2/kVA]) because most louvers have a 50% free area. For good convection, it is desirable to divide the opening areas in half, placing one-half near the ceiling and the remaining half near the floor. To provide for future equipment removal, if an areaway in a basement installation is large enough, it may be useful to increase the overall opening area and make the louver removable for access. A bird screen is also desirable.

Because outdoor air temperature varies, it is advisable to use a temperature-controlled, adjustable louver. In extremely cold climates, heat loss from the electrical equipment may not be sufficient to warm the room in winter. In such instances, a unit heater should be installed in the room with a thermostat set at 55°F (13°C).

27.9 TRANSFORMERS INDOORS: SELECTION

When transformers are installed indoors, they are subject to stringent *National Electrical Code* (*NEC*) regulations that are designed to make the installations intrinsically safe. These regulations are detailed in *NEC* Article 450. The essential considerations are presented herein.

(a) Oil-Insulated Transformers

These present a fire hazard when installed indoors because flammable oil can spread from a tank leak or rupture. To prevent this, most oil-filled transformers must be installed in a fire-resistant vault, the construction of which involves substantial cost. (See *NEC* Article 450 for exceptions.) Advantages offsetting this cost are an oil-filled transformer's small size, low first cost, low losses, long life, excellent electrical characteristics, low noise level, and high overload capacity. Despite these, the vault requirement typically restricts oil-filled units to industrial facilities and other structures where electrical considerations favor their use.

(b) "Less-Flammable" Liquid-Insulated Transformers

Transformers rated 35 kV or less that are insulated with a liquid ("less-flammable" liquid) whose fire point is not less than 300°C (572°F) may be installed indoors without a vault. A liquid confinement area is required, plus either a fire-extinguishing system or restrictions on the combustibility of the building's contents. The insulating liquids used are special types of silicones and hydrocarbons, and the transformer installation must meet all requirements for the specific liquid involved. Selection of these units achieves the electrical and physical advantages of oil-insulated units without the cost of vault construction and installation. The first cost of the units depends upon the fluid type and the specific electrical characteristics required. In general, they are somewhat less expensive than nonflammable fluid-insulated units with similar electrical ratings.

(c) Nonflammable Fluid-Filled Transformers

Certain nonflammable liquid coolants, called *askarels*, generally containing polychlorinated biphenyl (PCB), were once very widely used. Use of PCB coolants in new equipment is prohibited by federal regulation due to their negative environmental impact, and existing PCB transformers are being phased out. Newer nonflammable fluid coolants have increased the price of these transformers considerably (Table 27.4). Such units, nevertheless, have most of the advantages of oil-filled units and do *not* require a vault unless the voltage is very high. They do, however, require a sump or catch basin of sufficient capacity for all of the contained liquid. This and the high first cost are the negative aspects of this design.

(d) Dry-Type Transformers

These are the transformers of choice in the majority of indoor installations, despite having shorter life, higher losses, higher noise level, greater weight, and larger size than liquid-filled units. The principal advantages are simplicity of installation and almost unrestricted choice of location. As explained previously, using an underrated transformer (220°C [428°F] system, 80C° [144F°] rise), can reduce losses (heat) and extend life. Also, for a price premium, the noise level can be reduced.

Table 27.4 gives a comparison of the installed costs for the four classes of transformers discussed in this section.

27.10 TRANSFORMER VAULTS

A transformer vault is basically a fire-rated enclosure provided because of the possibility of fire caused by rupture of an oil-filled transformer case. This should not, however, be construed as implying that transformers are hazardous or delicate devices prone to faults. On the contrary, transformers are extremely tough, sturdy, long-lived, and capable of sustaining large and prolonged overloads. They are among the most reliable elements of an electrical system. However, faults do occur, and an oil-filled transformer is a potential fire hazard.

Transformer vaults should be located, to the extent possible, where they can be ventilated using outdoor air without flues or ducts. The combined

TABLE 27.4 Relative Installation Costs for a 300- to 1000-kVA Transformer

Transformer Type	Temperature Rise[a] (C°)	Relative Transformer Cost	Construction Cost	Total Relative First Cost
Oil-filled	65	1.00	50–100[b]	1.50–2.00
Less-flammable and nonflammable fluids	65	1.15–1.30	20–40[c]	1.35–1.70
Dry, ventilated	80	1.65	—	1.65
	80	1.50	—	1.50
	150	1.35	—	1.35
	150	1.20	—	1.20

[a]Transformers of equal temperature rise have approximately equal life and equal losses.

[b]Cost of the vault depends on local labor costs and size of the transformer. The relative cost decreases with increasing transformer size.

[c]Cost of catch basin. As in the case of a vault, relative cost depends on labor rates and transformer size.

Note: 65 C° rise = 117 F°; 80 C° rise = 144 F°; 150 C° rise = 270 F°.

net area of all ventilating openings (gross area less screens, louvers, etc.) should be as noted in the preceding section: not less than 3 in.^{2}/kVA (1935 mm^2/kVA) of transformer, but in no case less than 1 ft^2 (0.09 m^2). Further ventilation recommendations plus details of enclosure construction materials, fire rating, door and sill details, and other relevant design information are provided by *NEC* Article 450.

27.11 SERVICE EQUIPMENT ARRANGEMENTS AND METERING

Metering must be provided ahead (electrically) of the building service entrance switch(es). The metering is accomplished either at the utility or the facility voltage, and either at the service point or inside the building. The choice is generally left to the owner, with the understanding that interior meter equipment must be readily accessible to utility personnel. Although in increasingly large numbers of facilities regular meter reading is accomplished remotely, the meter equipment must still be available for utility company inspection and service.

If high-voltage service is purchased, then transformers and all other equipment beyond the service connection will be furnished by the owner. Conversely, if low-voltage service is purchased, all the equipment necessary to provide such low voltage is furnished by the utility. As might be expected, the billing rates for low-voltage service are *higher* than those for high-voltage service, in order to compensate the utility for the cost of providing and maintaining the needed step-down transformer and associated equipment. Therefore, it is often advisable for the owner of a large facility to investigate the economics of purchasing power at high voltage. Because many owners are not equipped to maintain high-voltage equipment, arrangements can sometimes be made to pay the utility to provide and maintain transformers while taking the cost advantage of high-voltage service.

For a single-occupant building or a building in which electric energy is included in the rental charge, only a single meter is necessary. Provision for such metering may be provided in the main switchboard, or the meter may be independently mounted. In both cases, the meter is furnished and installed by the utility company. Where submetering is required, such as in apartment houses, banks of meter sockets are installed to accommodate the multiple meters. Federal regulations forbid master metering in new multiple-dwelling constructions because it encourages energy waste (Fig. 27.7). Submetering should be considered in any facility where the energy consumption of specific building systems is of interest to conservation and/or ongoing commissioning efforts.

Fig. 27.7 *Three-section commercial submetering switchboard comprising a center service-entrance section rated 4000-A, 3-phase, 480-V maximum, equipped (usually) with a main switch or circuit breaker. Each of the end cubicles will accept six tenant meters, each on a 320-A 3-phase circuit, maximum, protected by an integral circuit breaker or fused switch. Tenant wiring enters the top or bottom of the board. Switchboards of this type can be installed on every floor of a large multitenant commercial office building. (Photo courtesy of Cutler-Hammer.)*

A low-voltage underground service detail as it would appear on a set of contract drawings, including relevant details, is given in Fig. 27.8. Note that here the service switch and meters are separately mounted.

27.12 SERVICE SWITCH(ES)

The purpose of electric service switch(es) is to disconnect the normal service to the building. (See Section 29.21 for a discussion of emergency electric service.) In the event of a fire, for example, the switch can be used to ensure that no electrical hazard will face firefighters. This disconnecting apparatus must be located at a readily accessible spot near

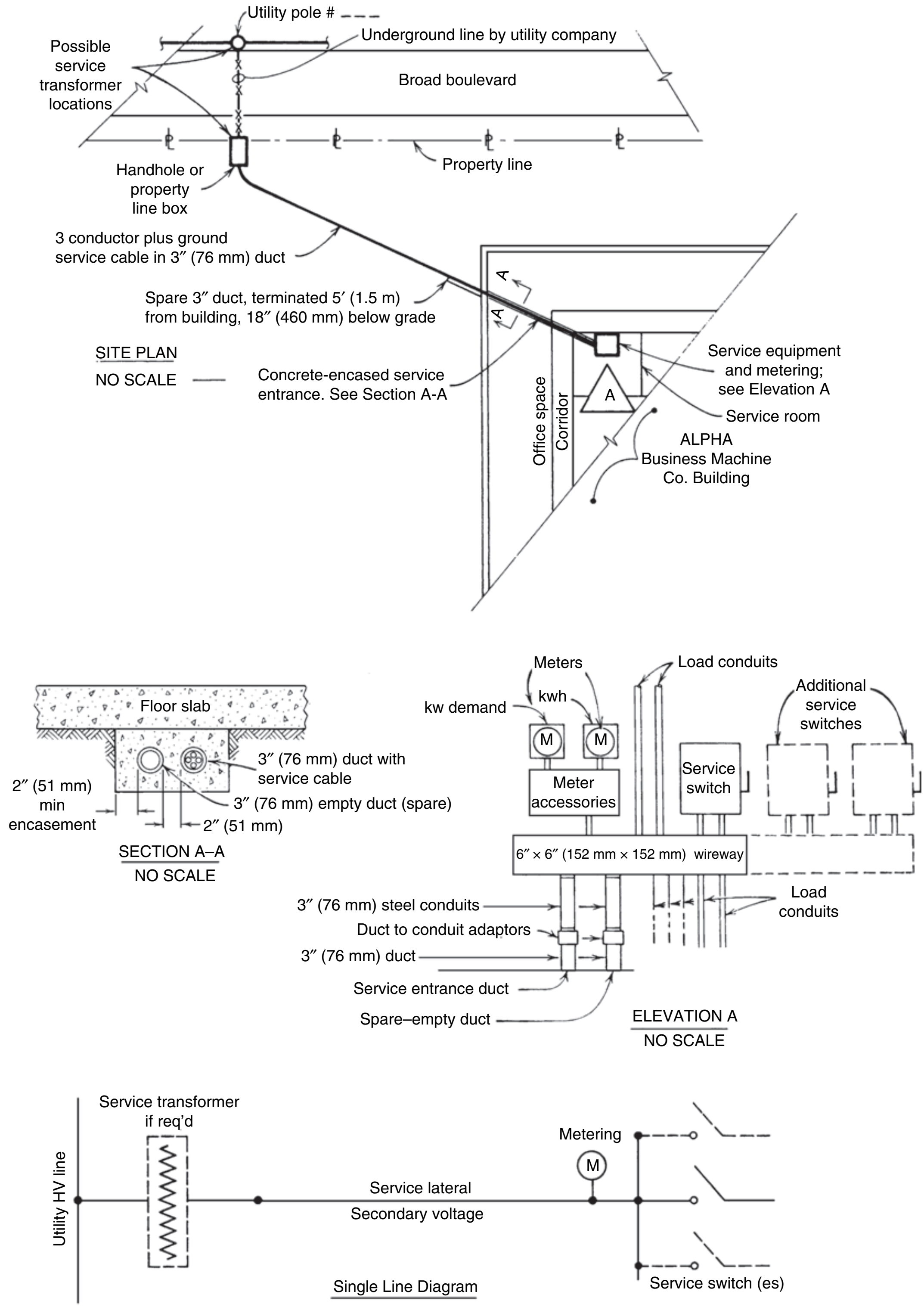
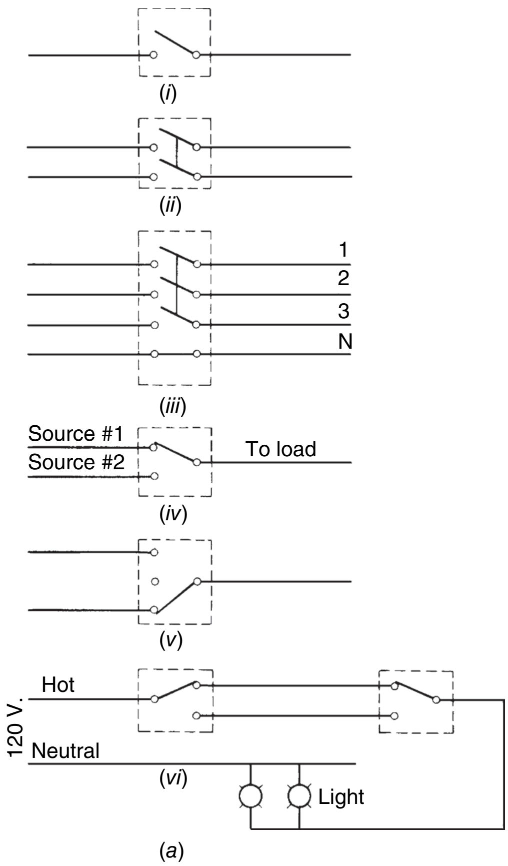


Fig. 27.8 *Typical electrical plan and details of an underground low-voltage service (600-V class) to an industrial facility. Note that the portion of underground service beneath the building must be encased in concrete. A service transformer (if required) could be mounted on the utility pole or on a pad at the property line.*

the point where the service conductors enter a building. If such a location is not feasible, service conductors may be run in concrete encasement under a building—and are considered "outside the building" up to the point at which they emerge from the floor in the building (see Fig. 27.8). At that point, the service disconnect switch must be installed. The service switch or, more accurately, the service-disconnecting means, may comprise between one and six properly rated switches. These are frequently assembled into a switchboard. Before discussing switchboards, however, a description of switches, circuit breakers, and fuses (the components of which switchboards are constructed) is in order.

27.13 SWITCHES

Traditional electrical switching devices are discussed in this and the following two sections. Mechanical switches close and open an electric circuit by physically moving two electrical conductors into contact with each other to close the circuit, and physically separating them to open the circuit. The motive force can be supplied by hand, an electrical coil, a spring, or a motor; the device name may change accordingly, but the action is the same. Solid-state switches perform the same electrical switching function but by a completely different process, without moving parts. They are discussed in Section 27.16.



(i) Single-pole single-throw switch.

(ii) Two-pole single-throw switch.

(iii) Three-pole and solid-neutral (3P and SN) switch.

(iv) Single-pole double-throw switch (also called, in small sizes, a 3-way switch).

(v) Single-pole double-throw switch with center "off" position (in control work called a hand-off-automatic switch).

(vi) Use of two single-pole, double-throw (3-way) switches for switching a lighting circuit from two locations

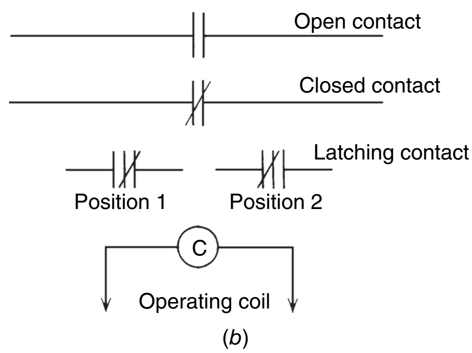


Fig. 27.9 *(a) Typical switch configurations. Note that switches are always shown in the open position. (b) Graphic representation of switch (contact) positions in a contactor or relay. Note that a latching contactor shows the switch in one of two positions to indicate the latching nature of the contactor.*

TABLE 27.5 Control Equipment Enclosures

NEMA Designation: Type	Description	Application
1	General-purpose	Dry, indoor use
2	Dripproof	Indoor, subject to dripping
3	Dust-tight, rain-tight, and sleet-resistant	Indoor/outdoor, where subject to windblown dust and water
3R	Rainproof and sleet-resistant	Outdoor, subject to falling rain, snow, and sleet
3S	Dust-tight, rain-tight, and sleet-proof	Outdoor, subject to windblown water, dust, and sleet; most severe exterior duty
4	Watertight and dust-tight	Indoor/outdoor, subject to water from all directions; not sleetproof
4X	Watertight, dust-tight, corrosion-resistant	Same as type 4 with added corrosion protection
7–9	Hazardous	Differing in application by class and group of hazardous use; see *NEC*
12	Industrial use, dust-tight, and drip-tight	Indoor only, general use, industrial and other "dirty" environments

An electrical switch is rated by current and voltage, duty, poles and throw, fusibility, and enclosure. The current rating is the amount of current that the switch can carry continuously and interrupt safely. Switches intended for motor control are also rated in horsepower (kW). The voltage rating of a switch is noted, as for other electrical equipment, by voltage class. Thus, a switch may be rated 250 V, 600 V, or 5 kV, as required. Switches intended for normal (occasional) use in lighting and power circuits are called *general-duty safety switches.* Switches intended for frequent interrupting, high-fault currents, and ease of maintenance are rated HD for *heavy duty.*

Figure 27.9*a* should clarify what is meant by the number of poles and throws of a switch. Unless otherwise noted, a switch is assumed to be single-throw. Because the *NEC* states generally that the grounded neutral conductor of a circuit should not be broken, most switches carry the neutral through unbroken by means of a solid link within the switch. This gives rise to the term *solid-neutral* (SN) *switch.* Switches are available in 1-, 2-, 3-, 4-, and 5-pole construction. Poles are indicated by a "P"; thus, 3-pole is written "3P," and so on.

A switch may be constructed with or without provision for fusing. If provided, the switch is fusible; if not, the switch is nonfusible. All individual enclosed switches are mounted in an appropriate cabinet. NEMA standardized the nomenclature and application of enclosures for all electrical control equipment, of which switches are only one item. Summarizing, the following adequately describes a switch: switch, HD, 3P & SN, 200A/150AF, 600 V, in NEMA 12 enclosure. This "translates" as a heavy-duty switch, 3 poles and solid neutral, 200-amp rating with 150-amp fuses, 600-V rating, in an industrial use enclosure (Table 27.5). Such a switch is illustrated in Fig. 27.10.

Fig. 27.10 *The internal construction of a heavy-duty, fused, 3-pole, 3-wire switch in an industrial NEMA 12 enclosure. Note the gasketing on the inside of the cover, which seals the sheet-steel box and makes it usable in environments containing lint, dust, dirt, sawdust, and the like. The external handle is a double-lockable indicating type for safety. (Courtesy of Siemens Energy & Automation, Inc.)*

27.14 CONTACTORS

A contactor is a switch. Instead of a handle-operated, movable blade, a contactor uses *contact* blocks of silver-coated copper, which are forced together to *make* (close) or are separated to *break* (open) a circuit. The common wall-mounted light switch is a small, mechanically operated contactor. A relay is an electrically operated contactor. Most contactors are operated by means of an electromagnet that causes the contacts to close. They open either by spring action or by gravity.

Contactor terminology is somewhat different from that of switches. Its condition when deenergized is its *normal* state. Thus, a contactor whose contacts are open when the coil is not energized is referred to as *normally open* (NO), whereas a contactor whose contacts are closed when deenergized is referred to as *normally closed* (NC). Units intended for motor connection are called *motor starters* and are discussed in Section 27.26. Current, voltage, and number of poles have the same nomenclature for contactors and relays as for switches.

The great advantage of contactors over switches is their facility for remote control. Switches must be manually thrown—or, in very special cases, thrown by a motor. The magnetic contactor, by contrast, is inherently a remotely controlled device, making it ideal for myriad control functions. It can be controlled by a manual or remote pushbutton or by automatic devices such as timers, float switches, thermostats, pressure switches, and so on. Because control can be both remote and automatic, contactors are universally used in the control of lighting, heating, air conditioning, motors, and the like. A graphic representation of contactors is shown in Fig. 27.9*b*.

27.15 SPECIAL SWITCHES

Many special types of switches are available. Most of these types are beyond the scope of this book, except for the following, which are used extensively in building design work.

(a) Remote-Control (RC) Switches

A contactor that latches mechanically after being operated is known as a *remote-control switch*. It differs from a relay in that the latching operation performs the dual function of latching the contacts and disconnecting the electric circuit. To unlatch the contacts, the electric circuit must be reenergized. Such a device is therefore also known as an *electrically operated mechanically held contactor*. This characteristic is advantageous where the position of the contacts will be maintained for a long period (as in a lighting control circuit) and it is undesirable to hold the contacts by the continuous energizing of a coil, as would be required with an ordinary relay. A typical unit is shown in Fig. 27.11, and a typical application is shown in Fig. 29.13. A common application of these switches is for controlling a "block" load, such as exterior lighting, whole-floor or whole-building lighting, and the like.

(b) Automatic Transfer Switch

This device, which is an essential part of all emergency and standby power arrangements, is

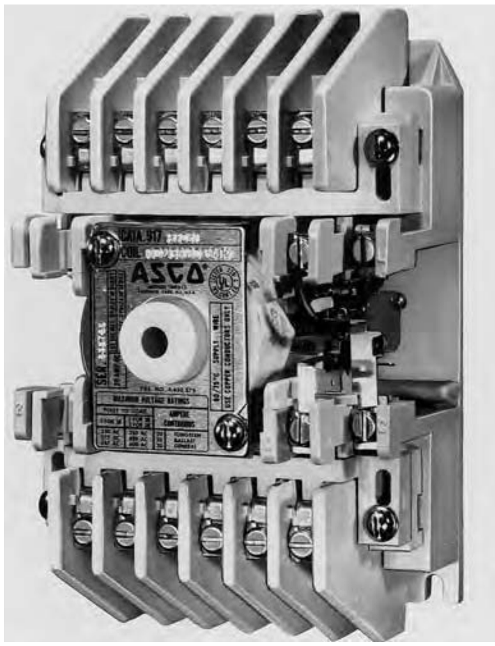


Fig. 27.11 *This remote-control switch (mechanically held, electrically operated contactor) is a 12-pole, 20-A, 600-V unit measuring approximately 7 in. H × 6 in. W × 4 in. D (178 × 150 × 100 mm), making it suitable for stud-wall mounting. Compact solid-state control modules are available that mount directly onto the unit and convert it to a flush, wall-mounted multicircuit programmable controller (see Section 27.16). (Courtesy of Automatic Switch Co.)*

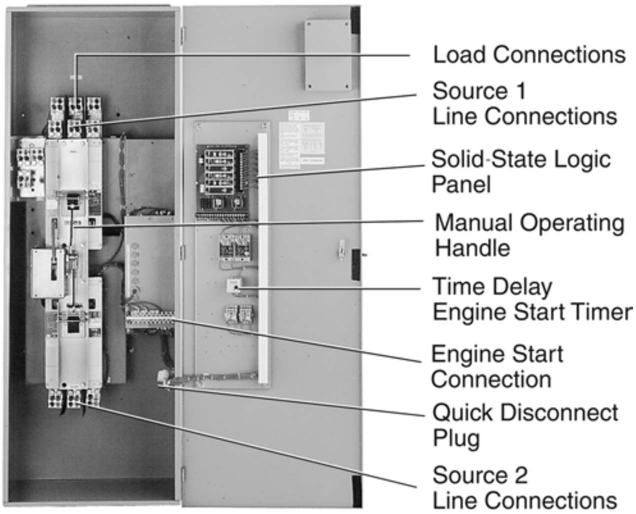


Fig. 27.12 *Automatic transfer switch with solid-state logic. The unit can be operated manually if required. It is equipped with engine-starting contacts, auxiliary contacts for monitoring, electrical safety interlocks, and automatic differential voltage sensing on the normal source. An 800-A, 3-phase unit of this design, in a NEMA indoor sheet-metal enclosure, measures 73 in. H × 26 in. W × 21 in. D (1.9 × 0.7 × 0.5 m) and weighs approximately 600 lb (272 kg). (Photo courtesy of Cutler-Hammer.)*

basically a double-throw switch—generally 3-pole—so arranged that on failure of normal service it *automatically transfers* to the emergency service. When normal service is restored, it automatically retransfers to it. (Retransfer can also be arranged to have a preset minimum delay, or it can be entirely manual.) The switch control is accomplished by voltage sensors that sense the condition of the service and operate the switch accordingly. Auxiliary devices can be added to the basic switch, the most common being emergency generator starting equipment. Figure 27.12 illustrates a typical unit. Transfer switches used in uninterrupted power supplies are normally solid-state devices because these involve no switching time lapse.

(c) Time-Controlled Switches

This category includes all switches whose operation is time-based. The timer can be either the familiar electromechanical device consisting of a low-speed miniature drive motor, to which some type of contact-making device is physically connected, or it can be a solid-state electronic timer, which in turn controls either a relay or a solid-state switch. The latter arrangement is the basis of all modern programmable time controls (Section 27.16), which find wide application in lighting control (Sections 16.14 and 31.27), energy management and automated building control (Sections 27.13 and 31.28), and clock and program systems (Section 31.14).

Motor-operated timers (other than hand-wound types) depend for their accuracy on power-line frequency, have moving parts that wear, must be reset after power outages (although some units have spring-wound reserve power motors), and become cumbersome and expensive with an increase in the number of controlled events. Electronic units are small, cool, quiet, independent of line frequency for accuracy (in many designs), able to function during power outages when equipped with a standby battery, and virtually unlimited in their event-control capacity. They have largely replaced mechanical timers except for the simplest applications (Fig. 27.13).

Fig. 27.13 *Adjustable time switch. This unit allows users to specify a singular, automatic "on" and "off" time.*

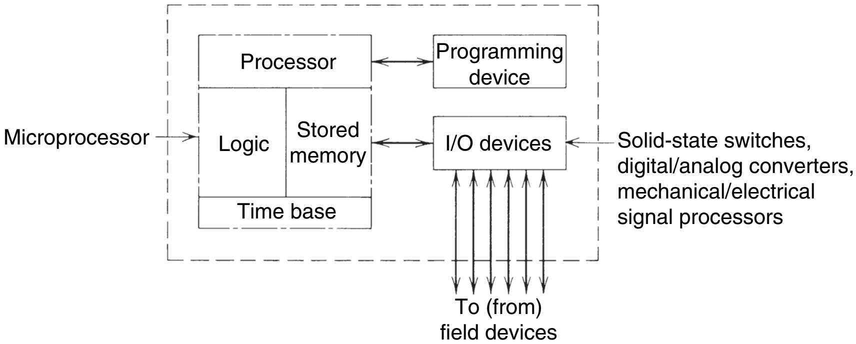


Fig. 27.14 *Block diagram of a programmable controller. These devices are designed to supervise field conditions continuously and are therefore used in industrial applications as well as for lighting and environmental system control.*

27.16 SOLID-STATE SWITCHES, PROGRAMMABLE SWITCHES, MICROPROCESSORS, AND PROGRAMMABLE CONTROLLERS

A solid-state switch is an electronic device with a conducting state and a nonconducting state, corresponding to a conventional switch in its closed and open positions. The change between the two states is accomplished by the application of a control signal (voltage). The change of state is instantaneous and noiseless, and occurs without arcing. The current ratings of solid-state switches are approximately the same as those of their mechanical counterparts, ranging from fractions of an ampere to hundreds of amperes. Voltage ratings are usually limited to secondary systems values (0 to 600 V) due to the nature of the semiconductors comprising the active elements of these switches, although higher-voltage equipment is available for special applications.

If an electronic timing device is added to a solid-state switch, a time-controlled electronic switch is created that functions exactly like the electromechanical time-based switches described in Section 27.15. These solid-state switches are independent of the utility line frequency for time control, and there are no moving parts to wear out. If a small, programmable memory circuit, in the form of an erasable programmable read-only memory (EPROM) chip is added, the device becomes a programmable time switch. The simplest of these are single-circuit 15-A devices intended to replace common wall switches (see Fig. 27.46).

A preprogrammed device, until reprogrammed, gives fixed, invariable instructions to a (multichannel) switch, as is the case with a programmable time switch. If a *microprocessor* (i.e., a logic/memory device programmed to *respond* according to a particular algorithm [control plan] to given input signals) is installed, a readily reprogrammable controller results (Figs. 27.14, 27.15, and 27.16). By definition, a *programmable controller* is an electronic device that

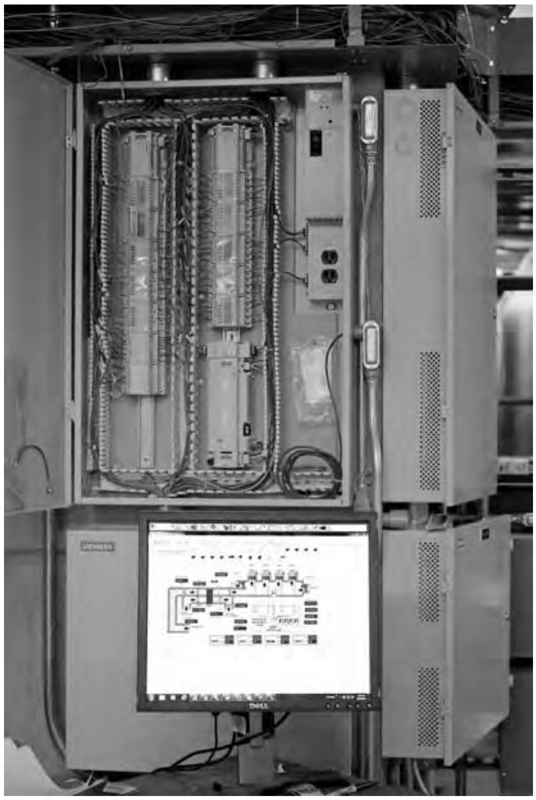


Fig. 27.15 *Programmable building monitoring system (BMS) from Siemens Corporation. Utilizing building system control devices, BMS software, and numerous sensors, the system allows for close monitoring of electric lighting, temperature, electrical demand, time signals, central control signals, and other energy-consuming inputs. (© Fred Tepfer; used with permission.)*

Fig. 27.16 *General-purpose programmable controller. The unit contains the central processing unit (CPU), random access memory (RAM), and power supply. Peripherals include the illustrated handheld programming unit and EEPROM (electrically erasable programmable read-only memory) module, and various computer/software interfaces (not shown). The unit illustrated, which measures approximately 10 × 9 × 3 in. (255 × 230 × 75 mm), has 16 input/output (I/O) circuits and an 885-word memory. It is readily adaptable to a variety of automated control processes in manufacturing, building control, and material handling. (Courtesy of Allen-Bradley Co.)*

uses a programmable memory chip for internal storage of instructions that in turn implement specific functions such as logic, timing, counting, and so on.

The internal control/memory is frequently referred to as a *microprocessor*; with respect to the overall programmable controller, it acts as a central processing unit (CPU). The programmable controller is therefore a special type of computer. It differs from a conventional computer in that its program is relatively short and exists in hardware (a microprocessor), whereas a computer reads its program, which can be very lengthy, into its memory from software. Furthermore, the programmable controller is designed for a specific function, whereas a conventional computer is a general-use calculating device that processes almost any type of software.

Programmable controllers have all but replaced the ubiquitous *hard-wired* relay panel in applications such as industrial control, elevator control, process control, and the like, because of the ease with which such a controller can be reprogrammed (in lieu of rewiring a relay panel), the speed and accuracy of control, and the vastly increased complexity possible. See Chapter 31 for definitions and for an explanation of the application of these devices to building control.

27.17 EQUIPMENT ENCLOSURES

Proper NEMA nomenclature, descriptions, and applications for the more common enclosures are found in Table 27.5. It is important to note that there is no enclosure described as WP or weatherproof. Equipment intended for outdoor use should be specified for installation:

1. In a type 3R enclosure to protect against rain (Fig. 27.17)

Fig. 27.17 *Rain-tight NEMA type 3R outdoor circuit breaker enclosure. This is the type usually intended when "weatherproof" is specified. (Courtesy of General Electric, U.S.A.)*

2. In a type 3S enclosure to protect against wind-driven rain and sleet
3. In a type 4 enclosure to protect against rain, wind-driven rain and sleet, plus splashing and condensation

Note also that the type 12 industrial enclosure is similar to type 1 except that it is gasketed for dust and drip resistance and therefore is well applied in *all* "dirty" indoor environments, including those in commercial and institutional spaces (see Fig. 27.10).

27.18 CIRCUIT-PROTECTIVE DEVICES

To protect insulation, wiring, switches, and other apparatus from the destructive effects of overload and short-circuit currents, an automatic means for opening the circuit is required. The two most common devices employed to fulfill this function are the *fuse* and the *circuit breaker*, the latter frequently abbreviated *c/b*.

(a) Fuses

The fuse is a simple device consisting of a *fusible* link or wire of low melting temperature that, when enclosed in an insulating fiber tube, is called a *cartridge fuse* and, when enclosed in a porcelain cup, is known as a *plug fuse*. Figure 27.18 shows common types of fuses. Plug fuses, such as those in residential use, are rated 5 to 30 A, 150 V to ground, maximum. Cartridge fuses of various designs are available up to 6000 A and 600 V.

(b) Circuit Breakers

A circuit breaker is an electromechanical device that performs the same protective function as a fuse and, in addition, acts as a switch. Thus, it can be used in lieu of a switch-and-fuse combination to both protect and disconnect a circuit. Most circuit breakers are equipped with both thermal and magnetic trips. The thermal trip acts on overload, whereas the magnetic trip acts on short circuit. These thermal and magnetic actions have inverse-time characteristics: That is, the heavier the overload, the faster the trip action. Modern circuit breakers in commercial and industrial applications are frequently equipped with solid-state electronic tripping control units, which provide fully adjustable overload, short-circuit, and ground-fault protection.

Air-circuit breakers are available in two types: the molded-case breaker and the large air-circuit breaker. Molded-case breakers consist of a complete mechanism encased in a molded phenolic case. A light-duty molded-case 50-A frame, plug-in circuit breaker is illustrated in Fig. 27.19*a*.

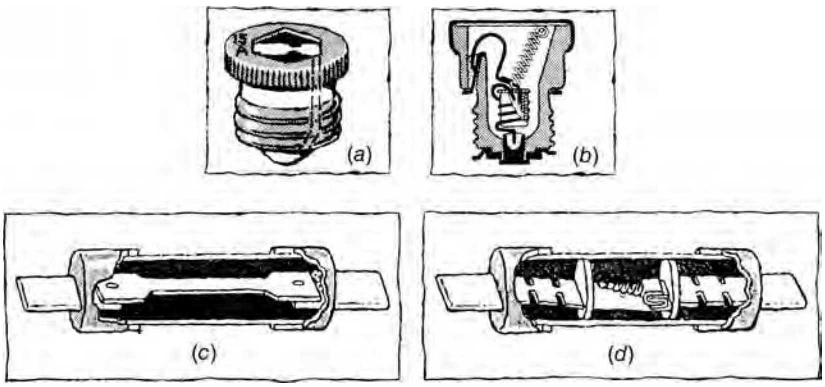
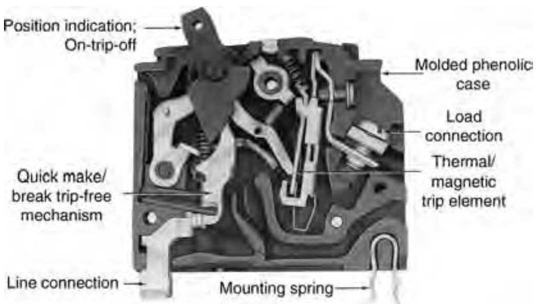


Fig. 27.18 *Plug-type fuses are made in two physical types. (a) The nonrenewable type with a standard (Edison) base screws directly into a standard socket. (b) Nonrenewable* NEC *type S fuses have a smaller base than type (a) and therefore require an adapter to fit into a standard socket. The adapter is current-rated and nonremovable. This prevents deliberate or accidental use of a type S fuse of incorrect rating. Type S is required in new construction where plug fuses are used. Both fuses shown are nonrenewable and must be replaced after blowing. The type S fuse shown in (b) is a dual-element time-delay fuse. Cartridge fuses are available in a variety of designs. Illustrated are (c) the nonrenewable, single-element type and (d) the nonrenewable, dual-element, time-delay type. Because fuses are inherently very-fast-acting devices, time delay must be built into a fuse to prevent blowing on short-time overloads such as those caused by motor starting. A dual-element fuse as shown in (b) allows the heat generated by temporary overloads to be dissipated in the larger center metal element, preventing fuse blowing. If the overload reaches dangerous proportions, the metal will melt, releasing the spring and opening the circuit. The notched metal portions of the fuse element, at both ends of the dual center element, provide short-circuit protection. The time required to clear (blow) a fuse is generally inversely proportional to the amount of current. In renewable-cartridge fuses, the spent (blown) element is replaceable, allowing reuse of the original outer cartridge and blade connectors.*

The molded-case breaker shown in Fig. 27.19*b* has a 400-A frame and can be equipped with an adjustable electronic tripping unit, ground fault trip, plus other features formerly available only on large air-circuit breakers. The large air-circuit breaker is a more complicated and highly adjustable device that can be used in applications that preclude the use of molded-case breakers. A modern solid-state adjustable trip controller for a large air-circuit breaker is shown in Fig. 27.20, along with a circuit breaker with a similar solid-state trip unit.



(*a*)

(*b*)

Fig. 27.19 (a) Essential elements of a plug-in-type molded-case circuit breaker are shown in cutaway. Details vary with breakers designed for specific applications. The unit shown is typical of breakers in the 50- to 100-A size. (Photo courtesy of The Square D Company.) (b) Heavy-duty molded-case circuit breaker, 400-A frame, 2- to 4-pole, 240–600 V. This circuit breaker is available with either a standard thermal-magnetic trip or an adjustable electronic trip with ground-fault protection. Among the accessories available are auxiliary contacts, shunt trip, undervoltage release, and an electrical solenoid operator that permits remote control of the breaker. The unit is suitable for individual or panelboard mounting. A typical 3-pole unit measures 5½ in. W × 10 in. H × 4 in. D (140 × 255 × 100 mm) and weighs about 12 lb (5.5 kg). (Photo courtesy of Cutler-Hammer.)

(*a*)

(*b*)

Fig. 27.20 (a) A multifunction microprocessor-based trip control unit for a large circuit breaker. It provides true root-mean-square (rms) sensing of phase and ground currents, selectable tripping characteristics, and trip alarm contacts. In addition, the unit can be used to display and transmit information on phase and ground currents. (Photo courtesy of Cutler-Hammer.) (b) Electrically operated large air-circuit breaker with electronic microprocessor-controlled trip unit and additional remote-control accessories. The illustrated unit, rated 2000 A, is shown before stationary (nondrawout) mounting in a switchboard. (Courtesy of General Electric, U.S.A.)

All breakers can be equipped with remote trip and auxiliary contacts, and all good breakers have trip-indicating handles and are *trip-free* (i.e., they will trip out harmlessly if closed on a short-circuited line). Low-voltage (600-V class) circuit breakers are available in frame sizes ranging from 50 to 4000 A and 1 to 3 poles. Their characteristics vary widely and are beyond the scope of this book.

(c) Characteristics of Fuses and Circuit Breakers

Although both fuses and circuit breakers are circuit-protective devices, their characteristics differ markedly, as seen in the following comparisons.

Fuses—Switch-and-Fuse Combination

ADVANTAGES
Simple and foolproof Constant characteristics (no aging) Initial economy Very high interrupting capacity (IC) No maintenance Instantaneous; energy-limiting
DISADVANTAGES
Fuses are single-pole only Necessity for storage of replacement fuses Nonrenewable (one-time operation) Nonadjustable Nonindicating[a] No electric or remote control[a] Not trip-free

Circuit Breakers

ADVANTAGES
Usable as switches Multipole No storage of replacements required Resettable Indicates trip Trip-free Remote-control potential Adjustable
DISADVANTAGES
Low to medium IC, except for special units Periodic maintenance required High initial cost Complex construction changes with age

[a]Can be accomplished with accessories.

These characteristics demonstrate that there is no single answer to the question "Which are preferable—fuses or breakers?" The answer depends upon the specific application involved and is often based on highly technical factors requiring detailed analysis. Circuit breakers are generally used in lighting and appliance panelboards.

27.19 SWITCHBOARDS AND SWITCHGEAR

A switchboard is a large, free-standing assembly of switches and fuses (and/or circuit breakers), which normally provides switching and overcurrent protection to a number of circuits connected to a single electric source. Metering and other instrumentation are also often included. A switchboard may be represented in a single-line diagram, as shown in Fig. 27.21. This equipment serves to distribute, with adequate protection, bulk power into smaller "packages." Thus, in a hydraulic analogy, the main buswork of the switchboard is equivalent to a main water supply header, the switches to on/off valves, the fuses to flow-limiting devices, and the feeders to subpiping connected to the main header.

Modern switchboards (Figs. 27.22–27.25) are all deadfront; that is, they have all circuit breakers, switches, fuses, and live parts completely enclosed in a metal structure. The operator controls all devices by means of pushbuttons and insulated handles on the front panel. Circuit breakers equipped with bayonet-type contacts, each mounted in a movable drawer (like the drawers of a standard letter file) in a switchboard, are described as the *drawout* type. This drawout arrangement facilitates emergency replacements, inspection, and repairs and is illustrated in Fig. 27.24.

No clear distinction is made between the terms *switchboard* and *switchgear*, although the terms suggest a sense of scale. Generally, low-voltage switchboards with large circuit breakers and all high-voltage equipment (above 600 V) are referred to as *switchgear*. When molded-case circuit breakers are utilized in a switchboard, it is often referred to as a *building-type switchboard*.

Recommended minimum space requirements for various types of switchgear are shown in Fig. 27.26. Working space around all types of electrical equipment must meet the

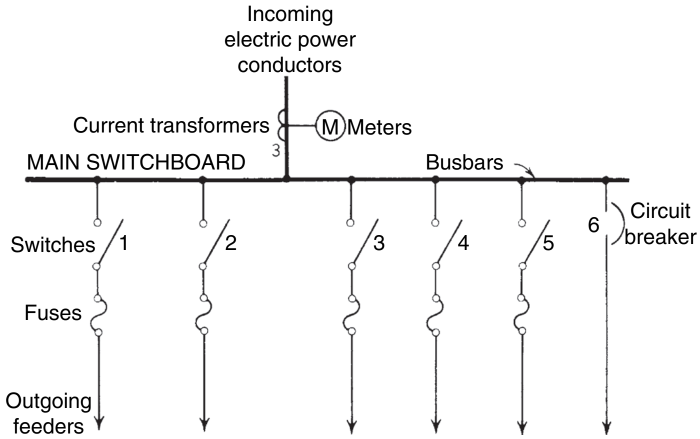


Fig. 27.21 *One-line diagram of a typical switchboard. Switches are normally shown in the open position. Switches must be on the line (supply) side of fuses. Each line in a single-line diagram represents a 3-phase circuit. If circuit breakers were used, the entire board would be composed of units as depicted in circuit 6.*

requirements of *NEC* Article 110. Main metal-clad switchgear for commercial, industrial, and public buildings is almost invariably located in a basement and housed in a separate well-ventilated electrical switchgear room. Smaller subdistribution switchboards require no special room. A wire screen enclosure to prevent tampering or vandalism plus a large "DANGER—HIGH VOLTAGE" sign are usually adequate. The architect must provide adequate exits, hallways, and/or hatches for the installation and removal of all equipment. Specifications for switchgear should state the maximum overall dimensions of sections that will be transported and installed in one piece.

When switchgear is to be installed outdoors, one of three methods is employed: build a small structure to enclose normal indoor gear, utilize

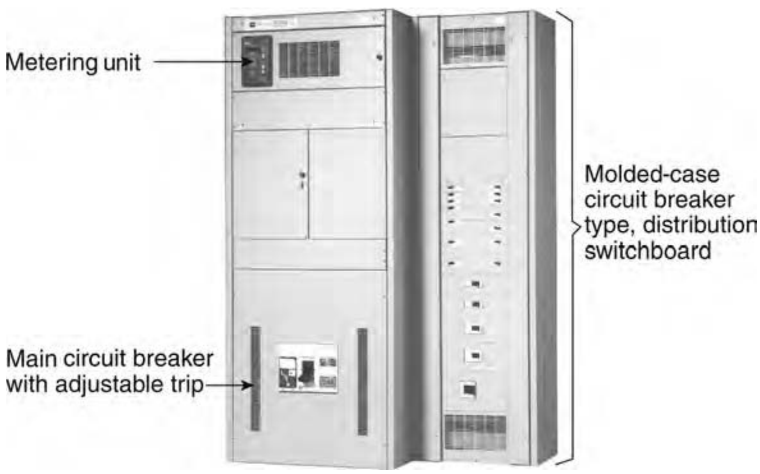


Fig. 27.22 *Free-standing, indoor-service, low-voltage (600-V) switchboard with group-mounted, fixed molded-case circuit breakers. The deeper section contains the service entrance main circuit breaker (maximum 3000 A) plus instrumentation. Section width varies from 30 to 45 in. (0.75 to 1.1 m) and depth from 18 to 36 in. (0.5 to 0.9 m), depending upon the main circuit breaker rating. The smaller section contains branch circuit breakers. All units are 90 in. (2.3 m) high. (Photo courtesy of Cutler-Hammer.)*

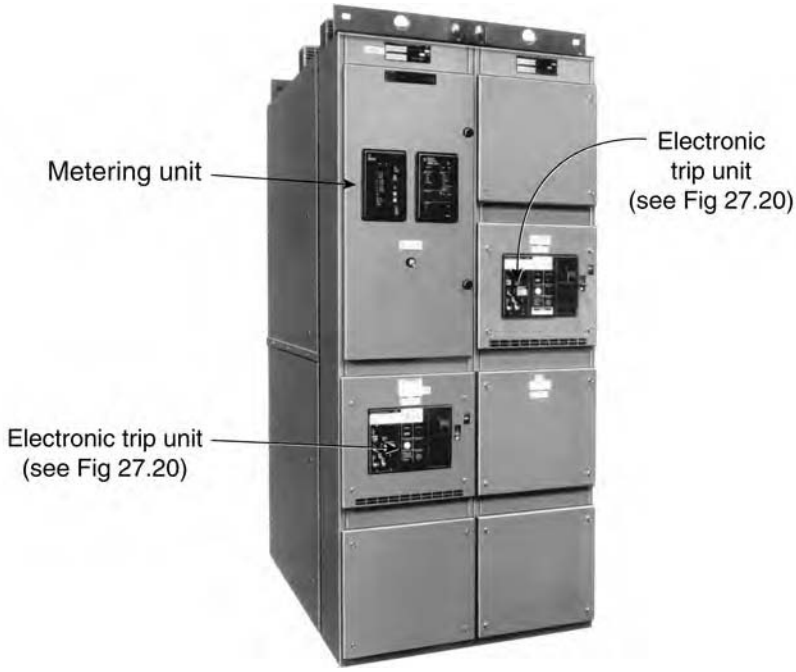


Fig. 27.23 *Metal-enclosed, indoor, low-voltage power switchboard with fixed or drawout large circuit breakers. Maximum bus capacity is 5000 A. Section dimensions vary with the size and type of contained equipment. All units are 90 in. (2.3 m) high. Each circuit breaker is equipped with a microprocessor-controlled trip unit. It can be seen clearly on the front of each unit. In addition, another programmable solid-state metering/analysis unit can be seen at the left of the top compartment of the entry (left) cubicle of both this switchgear and the switchboard in Fig. 27.22. (Photo courtesy of Cutler-Hammer.)*

Fig. 27.24 *Three sections of medium-voltage metal-clad drawout switchgear, suitable for indoor use as shown and for outdoor use with cabinet modification. Voltage ratings are 5–27 kV; current ratings are 1200–3000 A. Each indoor section measures 36 in. W × 95 in. H × 96 in. D (0.9 × 2.4 × 2.4 m) and contains two compartments for circuit breakers and/or instrumentation. Due to the drawout characteristic (shown), a 72-in. (1.8-m) front aisle is required. Similar outdoor aisle-less switchgear measures 36 in. W × 115 in. H × 101 in. D (0.9 × 2.9 × 2.6 m). (Photo courtesy of Cutler-Hammer.)*

weatherproof outdoor gear, or utilize switchgear that is built into its own exterior enclosing structure, as seen in Fig. 27.25. These housings are equipped with heating and lighting and often prove to be the most economical choice.

27.20 UNIT SUBSTATIONS (TRANSFORMER LOAD CENTERS)

An assembly, comprising a primary voltage switch-and-fuse or circuit breaker, a step-down transformer, meters, controls, buswork, and secondary (low-voltage) switchgear, is known as a *unit substation* or a *load-center substation*. Its function is to accept an incoming high-voltage power supply, transform the high voltage to a voltage that can be utilized in the facility, and distribute the low-voltage power through associated low-voltage (secondary) switchgear. A dimensional physical sketch of a typical unit substation, along with its electrical single-line diagram, is shown in

Fig. 27.25 *Four-bay (section), power-operated, high-voltage service entrance switchgear rated 13.8 kV, consisting of (see the single-line diagram inset, and reading from left to right) a fused feeder section, two bays with parallel incoming lines and automatic transfer in the event of power failure, and a second switch and fuse feeder section. Fuses are electronic, with circuitry designed to provide a trip signal when excessive current is sensed, rather than simply relying on the thermal characteristic of a fusible element. This gear, which measures 93 in. H × 172 in. W × 44 in. D (2.4 × 4.4 × 1.1 m) and weighs 8000 lb (3630 kg), is suitable for interior or exterior installation.*

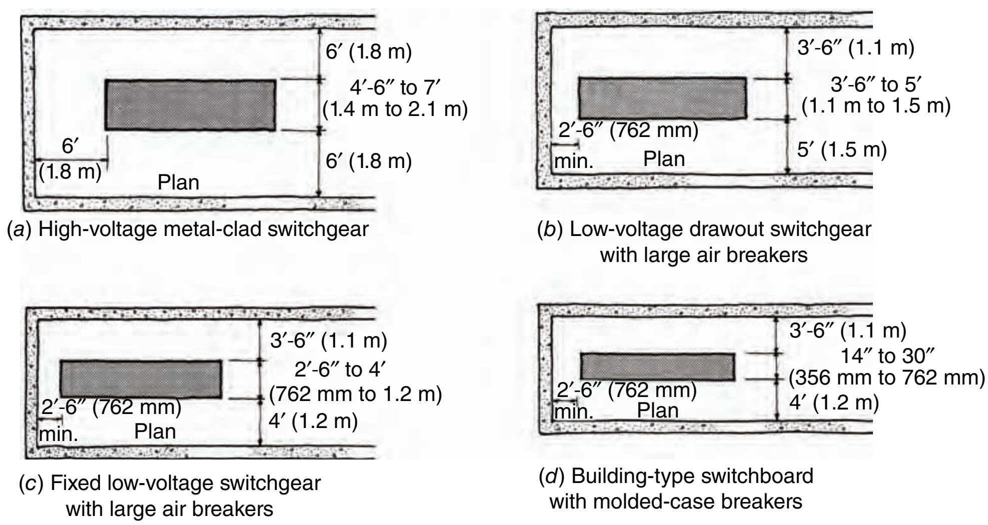


Fig. 27.26 *Typical nominal switchgear space requirements. Each room should have two doors when switchgear is connected to high-capacity systems or operates at high voltage. Switchgear is shown in plan view. For detailed space requirements, see* NEC *Article 110.*

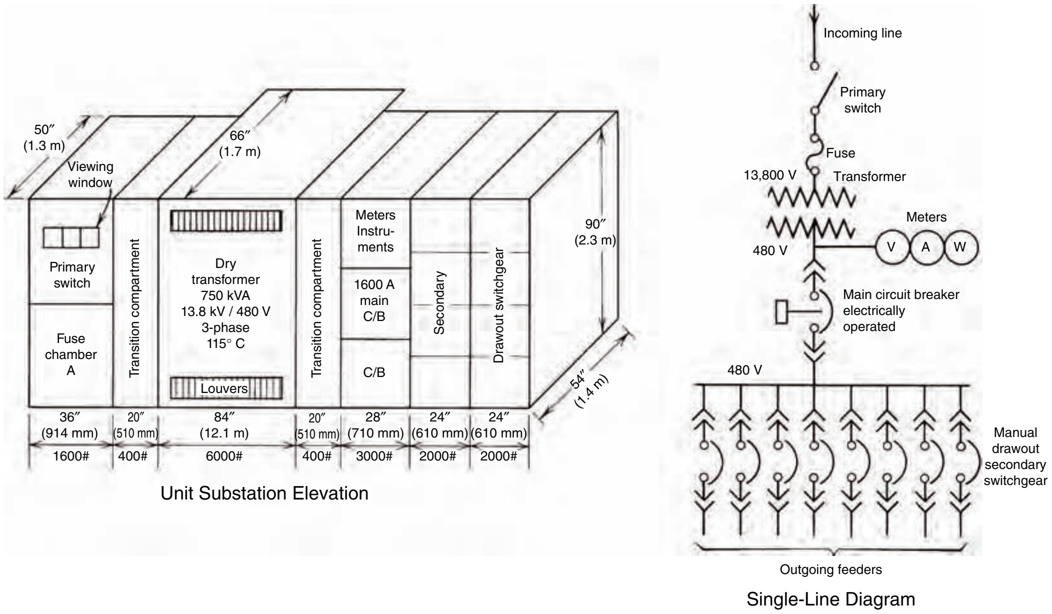


Fig. 27.27 *Approximate sizes and weights of a typical large single-ended unit substation. Such a unit would supply a building with a maximum demand of 750 kVA. The incoming 13,800-V cables enter cubicle A and connect to the primary switch and fuses. The load side of the fuses connects to the transformer, which in turn connects to the secondary switchgear. The main secondary switchgear then feeds various switchboards and panelboards distributed throughout the building.*

Fig. 27.27. Equipment is available for indoor or outdoor installation.

If installed indoors, the location of a unit substation is governed by the type of transformer utilized, as explained in the discussion on indoor transformer installations. For this reason, almost all indoor unit substations utilize dry-type (air-filled) transformers. A basement location is most often selected, with ventilation requirements as detailed previously. Access should be restricted to authorized persons. Unit substations are selected to obtain the economies inherent in prefabricated construction using coordinated components.

27.21 PANELBOARDS

An electrical panel, or *panelboard*, serves essentially the same function as a switchboard except on a smaller scale. It accepts a relatively large block of power at some downstream point in a system and distributes it in smaller blocks. Like a switchboard, it comprises main buses to which are connected circuit-protective devices (breakers or fuses) that feed smaller circuits. The panelboard level of a system usually represents the final distribution point, thence feeding out to the branch circuits that contain the electrical utilization apparatus and devices, such as lighting, motors, and so on. Small panels, particularly in residential work, are frequently referred to as *load centers*.

The panelboard components—the buses, breakers, and so on—are mounted inside an open metal cabinet called a *backbox*. The backbox is prefabricated with knockouts at the top, bottom, and sides to permit connection of conduits carrying circuit conductors (Fig. 27.28). The main feeders that supply power to the panel's busbars enter through the large knockouts in the metal backbox, as in Fig. 27.28. Details of panelboard construction are presented in Fig. 27.29. A panel may be equipped with a main circuit breaker whose function is to disconnect the entire panel in the event of a major fault. Figures 27.28 and 27.29 show panelboards with only branch circuit devices and no main breaker or switch. These panels are described as "lugs in mains only," which means that the panel has only connectors (lugs) on the main busbars for

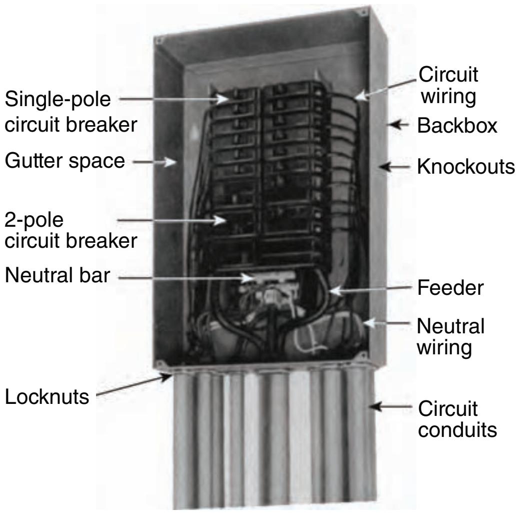


Fig. 27.28 *A wired panelboard is shown with the cover removed. This panel is single-phase, 3-wire, meaning that it has two phase bars and a neutral (note the three heavy feeder cables). Lighting and appliance panels such as this are 4½–6 in. (115–150 mm) deep, 16–20 in. (400–500 mm) wide, and of sufficient height to accommodate the devices. The top device may be no higher than 78 in. (2 m) above the finished floor (AFF) and the bottom one no lower than 18 in. (450 mm) AFF to meet* NEC *requirements.*

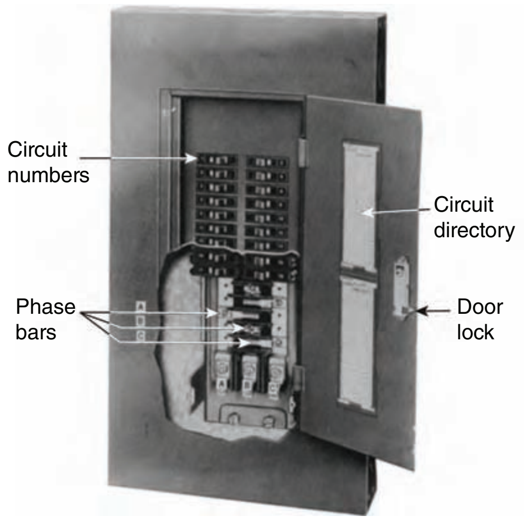


Fig. 27.29 *Cutaway of a typical lighting and appliance panelboard. Branch circuit-protective devices are normally arranged in two vertical rows, even in 3-phase panels. The circuit directory on the inside of the panelboard door gives a brief description of the loads connected to each branch circuit breaker.*

connection of the main feeder cables and no main protective device. The backbox is closed with a protective front panel with an access door. Three basic panelboard types are shown in Fig. 27.30.

The line terminal of each circuit-protective device (breaker or fused switch) is connected to the busbars of the panelboard. The load terminal of the device then feeds the outgoing branch circuit. This is shown schematically in Fig. 27.31, which is a line-drawing representation of an electrical panelboard. Notice that the circuit breakers are arranged in two vertical rows, corresponding to actual construction practice. In the illustrated line drawing, a 3-phase panel is shown (i.e., three-phase busbars and a neutral bar). The busbars of the panelboard are energized by a feeder from a switchboard or large power distribution panel.

Panelboards are described and specified by type, bus arrangement, branch breakers, main breaker, voltage, and mounting—although not necessarily in that order. A typical description might be: lighting and appliance panel, 3-phase, 4-wire; 200A mains; main c/b, 225A frame, 150A trip. Branch breakers—all 100A frame; 8 ea. SP-20A, 4 ea. 2P-20A, 4 ea. 3P-20A; flush with hinged locked door.

27.22 PRINCIPLES OF ELECTRIC LOAD CONTROL

The key to energy conservation and electric demand limitation is load control. In the past, the extent to which both of these desirable outcomes were implemented was essentially an economic decision: Would the savings in electricity costs justify the expense of installing the required control? Today, and increasingly in the future, building codes (and a desire to exceed the codes) will mandate energy-consumption limitations. ASHRAE Standard 90.1 requires lighting controls in nonresidential buildings, and the trend toward additional and more stringent requirements is clear. The rationale for load control to limit demand charges was discussed previously.

Lighting control strategies are discussed in Chapter 16. The essential control principle that applies to all loads, not only to lighting, is

Bolt-on and Plug-in
240 V ac Maximum
(*a*)

Circuit Breaker Panelboard
(*b*)

Fusible Panelboards
(*c*)

Fig. 27.30 *Three different designs of panelboards. (a) Circuit breaker–type panelboard using bolt-on and plug-in molded-case circuit breakers 1- to 3-pole, 15–100 A. A main device of up to 400 A can be installed. The panel is rated for 240 V AC. The illustrated panel, which is arranged for surface mounting, measures 30 in. H × 20 in. W × 5¾ in. D (760 × 510 × 145 mm). (b) Circuit breaker distribution-type panelboard with maximum bus ratings of 1200 A and 600 V AC. Branch circuit breakers can be 15–100 A, single-pole and 15–1200 A, 2- or 3-pole. These panels are free-standing but can be wall-mounted, provided that the highest device does not exceed 6 ft, 6 in. (2 m) AFF. Similar units are available with a front door. Depending upon the contents, cabinets can be 24–36 in. (610–915 mm) W × 60–90 in. (1.5–2.3 m) H × 6–8 in. (150–200 mm) D. (c) Switch- and fuse-type distribution panelboard, free-standing, with ratings similar to those of the circuit breaker type in (b). Cabinets are 36–44 in. (915–1115 mm) W, 74–90 in. (1.8–2.3 m) H, and 10½ in. (265 mm) D. (Photos courtesy of Cutler-Hammer.)*

straightforward: The load is switched or modulated in response to a control signal (Fig. 27.32*a*). In terms of hardware, the process is somewhat more complex. Figure 27.32*b* shows in principle the equipment and wiring required in a common application: time control of exterior lighting, with photocell override. Figure 27.33 shows a more complex arrangement for area lighting control with local override, as might be installed in conjunction with a commercial office building. In each case, there are signal-initiation devices, one or more relays that perform the actual electrical switching, and control and power wiring—in addition to the main power wiring from the panelboard.

Many past users found that the payback from reduced electric billing was insufficient to cover the control equipment cost, particularly where local and/or remote override was required, and as a result relied on inefficient and generally ineffective manual control. That option, however, is limited today and will become even more so in the future. As a result, a more economical way to accomplish the required control functions was

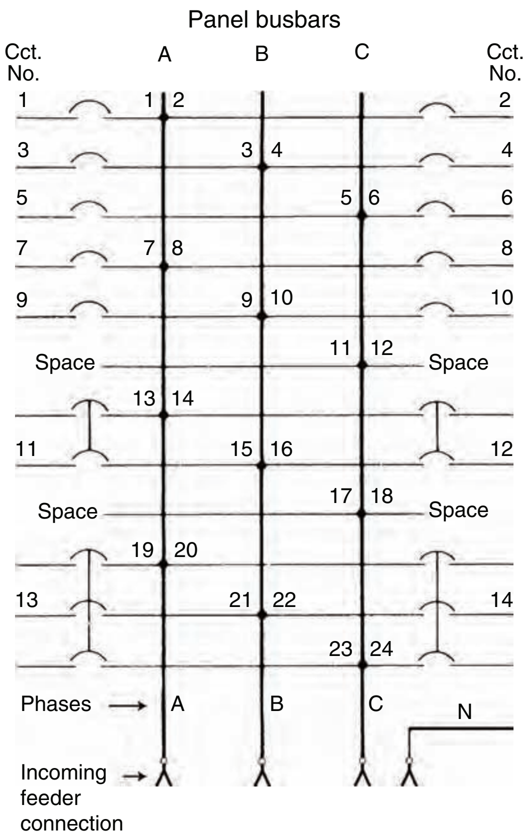


Fig. 27.31 *Typical schematic diagram for a panel. Note that single-pole, 2-pole, and 3-pole circuit breakers are connected to 1-, 2-, and 3-phase buses, respectively. They supply 120-V 2-wire, 120/208-V 3-wire, and 120/208-V 3-phase 4-wire, respectively. This panelboard would be described as a 3-phase 4-wire lighting and appliance panel, with 10 SP, 2-2P, and 2-3P circuit breakers, lugs in mains only. The voltage of the panel and the ampere ratings of buses and all circuit breakers would then be specified.*

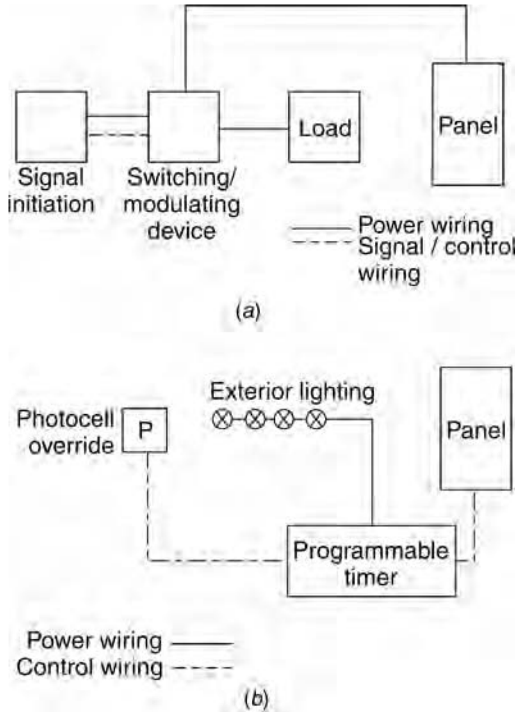


Fig. 27.32 *(a) A low-voltage lighting control system always includes the elements shown. Signal initiation can come from a sensor such as a photocell or from a control device such as a timer, an override signal, a central computer signal, and the like. The signal activates the power-switching device, which in turn switches or modulates the load. The power source is always the associated lighting panelboard. (b) Schematic arrangement of a control system for exterior lighting. If the system is compact, a switching timer would be used. For a spread system, timer-controlled switching relays at each fixture would be used with attendant additional control wiring. Grouping of the fixtures into different control sequences (road, parking lot, building entrance, etc.) further complicates the wiring.*

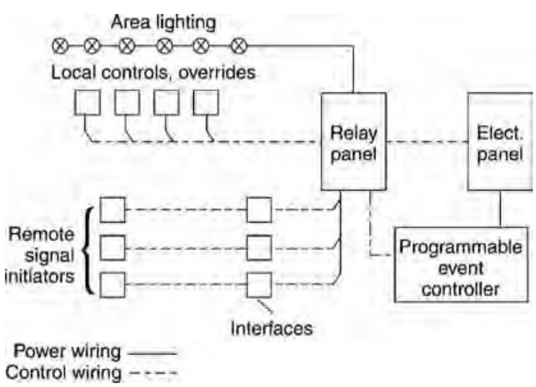


Fig. 27.33 *Schematic diagram showing equipment and connections that might be used for control of a block of lighting in a large commercial building. The wiring can be even more complex and extensive if control of smaller lighting groups is desired or if control is desired from more than one location.*

developed, thanks in large measure to modern miniaturized programmable control elements. These can be installed directly in the lighting panelboard. Such a panel is known in the industry by the generic term *intelligent panelboard* and by various trade names that identify specific manufacturers.

27.23 INTELLIGENT PANELBOARDS

The idea behind an intelligent panelboard is straightforward. If many of the necessary electric load control and switching functions are incorporated into the panelboard by use of a compact, centralized, programmable microprocessor, the corresponding external devices and associated wiring are eliminated. The switching function is made possible by the use of motor- or solenoid-operated panel circuit breakers, thus taking advantage of their switching capability and eliminating the need for relays, contactors, and switches. The internal central controller permits local programmable control of each panel circuit breaker *individually*.

This central panel-mounted controller can also accept signal data from individual remote or network sources and can provide status reports, alarm signals, operational logs, and local bypass and override functions. Control cards in an adjacent cabinet, connected to the controller, can provide local switch override, daylight dimming and on/off control, telephone override energy control, electric demand control, and networking. With careful planning, the high initial cost of an intelligent panelboard can be offset by elimination of remote relays, relay panels, programmable time switches, remote-control switches, and all of their associated wiring. Simplified and improved facility operation, plus reduced maintenance costs and electric bills, are additional benefits that can be achieved with proper application and careful design. Figure 27.34 shows the essential elements of an intelligent panelboard and a typical network arrangement using the remote-control capabilities of such panels.

27.24 ELECTRIC MOTORS

Motors are frequently supplied along with the equipment they drive (such as fans, blowers, and so on) as part of a complete package. The actual choice of motor is left to the driven-equipment supplier, because the supplier is presumed best qualified to select a motor that will optimally match the driven-equipment requirements, for whose proper operation the supplier is responsible. In practice, however, a supplier is frequently guided primarily by price—low first cost being a recurring theme in building design and construction, very often to the detriment of low life-cycle cost. The designer, therefore, should be sufficiently knowledgeable so that the best motor for the application can be specified. The following sections are written with that purpose in mind, and are primarily concerned with application.

(a) Direct-Current Motors

These motors are not normally used in building work. The fine speed control (for which they were primarily used) is now available, more economically, with AC motors, as explained in Section 27.26.

(b) Alternating-Current Motors

These motors fall into three general classifications: poly-phase induction motors, poly-phase synchronous motors, and single-phase motors. Within these categories there are further subdivisions. Of these many types, most motors used in building equipment are squirrel-cage induction machines; therefore, this type is studied in some detail.

(c) Squirrel-Cage Induction Motors

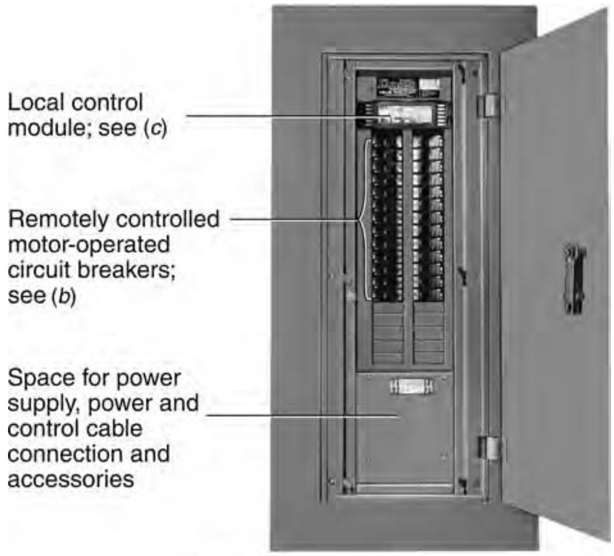
This type of induction motor owes its interesting name to an early design in which the rotor consisted of a group of bars welded together into a cylindrical cage-type shape. The design, invented by Nikola Tesla, is basically unchanged today except for refinements. Squirrel-cage motors are manufactured in four different NEMA designs to meet different application requirements. Of these the most common are:

Type B: Standard design, high efficiency and high power factor, normal torque; applicable to fans, blowers, and pumps

Type C: High starting torque, fair efficiency and power factor; applicable to compressors, conveyors, and other devices that start under load

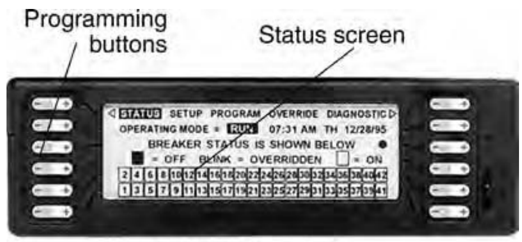
A motor nameplate gives important information on a motor that is not self-evident:

1. *Type*: This is the manufacturer's designation and indicates primarily the enclosure. Common enclosures are open drip-proof, totally enclosed, fan-cooled, and weather-protected.
2. *Duty (time rating)*: Continuous or intermittent.
3. *Service factor*: Permissible overload; generally 15%.
4. *kVA code*: Indicates by a letter the maximum starting current per horsepower. This is useful in selecting motor-protective devices. More recently, actual locked rotor amperes have been given.
5. *Frame*: A NEMA standard number that indicates the motor's physical dimensions.

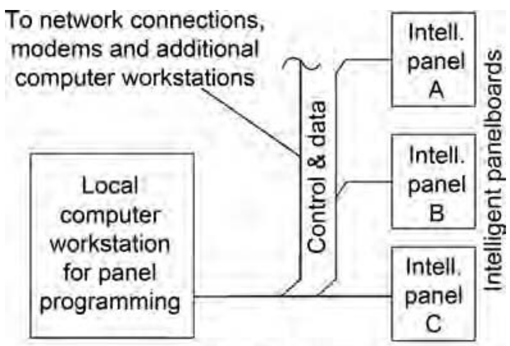


(*a*) Intelligent panelboard

(*b*) Single-pole motor-operated circuit breaker



(*c*) Control module



(*d*) Block diagram

Fig. 27.34 *(a) This intelligent panelboard contains (from top to bottom) a microprocessor control module, 26 single-pole, remote-controllable (motor-operated) circuit breakers, space for 10 additional poles, and a compartment containing a DC power supply (for circuit breaker operation) and accessories. (b) This motorized single-pole circuit breaker can be manually or remotely controlled. Electric operation latches the circuit breaker so that in the event of power failure, all breakers remain in their pre-outage condition. The illustrated unit is a 100-A frame, 20-A trip unit. A status window on each unit displays its condition, while electronic sensors in each unit sense voltages and indicate on the control panel the status of each unit. (c) The control module, mounted at the top of the panelboard, is equipped with programming buttons that allow control of each circuit breaker individually. The illustrated basic control module programs and controls essential functions, including configuration, circuit breaker status, resetting, zoning, settings for hardware characteristics, override modes, screen selection, and self-diagnostics. Additional control modules (not shown) supply time-based programming, logging functions, and timed functions. The illustrated breaker status screen is one of five displays. The others are setup, program, override, and diagnostic screens. (d) Intelligent panels can be incorporated into a large control network by use of interface connections of various types (not shown). The illustration is a block diagram showing one of the networking possibilities. (Photos courtesy of Square D.)*

6. *Motor voltage*: The standard motor voltages are 208, 230/460, and 575 V. Induction motors generally operate satisfactorily at +/– 10% voltage. Only 208-V motors should be used on 208-V systems because the actual line voltage may be as low as 200 V. Using a 230-V motor on a 200-V circuit will result in sharply reduced torque, increased temperature rise, and poor overload capacity.
7. *Motor nominal full-load efficiency*: As stated; a requirement of ANSI/ASHRAE/IESNA Standard 90.1 and EPACT.
8. *Design letter*: Indicates inherent motor design characteristics.

(d) Electric Motor Energy Considerations

The federal Energy Policy Act of 1992 (EPACT; subsequently updated/amended/morphed) required that the most common designs of induction motors, accounting for 70% to 80% of all poly-phase induction motors sold in the United States, meet higher efficiency and power-factor standards. Specifically, these efficiency standards apply to single-speed, poly-phase, squirrel-cage induction motors, designs A and B, continuous rating, and operating at 230/460 V, 60 Hz. These motors are known as *premium efficiency* or *PE* motors.

The decision on whether to use a PE motor in applications not mandated by law is essentially an economic and environmental one. Many motor manufacturers make available straightforward software that enables a designer to rapidly make a detailed life-cycle cost comparison among motor types, with operating time, loading, first cost, energy and maintenance costs, and so on, as the variables. As a guideline, motor applications involving low starting torque and frequent motor operation at partial load are likely candidates for short payback periods on the price premium of PE motors. Higher efficiency also results in reduced consumption of the typically nonrenewable energy resources used to generate electricity.

27.25 MOTOR CONTROL STANDARDS

American designers and equipment manufacturers historically utilized motor control equipment manufactured to NEMA standards exclusively. It was also common practice in the construction industry to split the motor and motor-control package by having equipment manufacturers supply the motorized equipment while the electrical construction contractor supplied the motor control equipment. Few coordination problems between controller and motor drive were encountered because control equipment sized and built to NEMA standards is large, heavy duty, and applicable to a wide range of motor sizes and characteristics.

The International Electrotechnical Commission (IEC) is a technical organization with around 60 full (including the U.S.) and 22 associate member nations. It develops recommended standards for electrical equipment, including motor controls. The IEC design concept regarding a motor and its controller involves close coordination. Such application-sensitivity—coupled with flexible ratings for a single piece of equipment, depending upon its application—makes equipment built to IEC standards smaller, lighter, and cheaper than similarly rated equipment built to NEMA standards. As a result, many U.S. manufacturers utilize IEC motor controls in conjunction with their motive equipment, particularly on international jobs. Because U.S. architects, engineers, and contractors are involved in a large number of construction projects outside of the territorial United States, those responsible for designing, specifying, and purchasing electrical equipment in general, and motor control equipment in particular, should be aware of the comparative characteristics of NEMA-based and IEC-based equipment.

27.26 MOTOR CONTROL

(a) Fundamentals

A conventional AC motor controller is basically a contactor (see Section 27.14) designed to handle the heavy inrush currents involved in starting an AC motor. Its function is twofold: to start and stop the motor and to protect it from overload. These two separate and distinct functions are accomplished by combining a set of contacts for on/off control with a set of thermal overload elements for overload protection in a single unit. When the contacts are operated by hand, the controller is called a *manual starter*; when the contacts are operated by a magnetic coil controlled by pushbuttons, thermostats, or other devices, the unit is known as a *magnetic controller* or, simply and more commonly, a *magnetic starter*.

Motors of 1 hp (0.75 kW) or less are generally controlled by a manual switch that contains an overload protection device. It is advisable to utilize such a device for all fractional horsepower (low kW) motors.

Most starters are of the full-voltage across-the-line (ATL) type; that is, the contacts place the motor directly onto the line, and the motor starts up immediately. When such a procedure is undesirable because of voltage dip and flicker caused by the large inrush current or because of utility company limitations, a reduced-voltage starter, sometimes called a *compensator*, is used. These units initially apply reduced voltage to the motor, thus reducing the starting inrush current and line voltage drop. This in turn reduces dimming of lights, flicker, and other undesirable effects.

Older reduced-voltage starters use a stepping arrangement whereby voltage is increased incrementally, thus limiting inrush current. Unfortunately, starting torque is also limited, thus restricting the application of these starters. Solid-state starters that have been available since the late 1980s provide continuous (stepless), controlled motor starting. These units not only limit inrush current, but also, by adjusting the acceleration time, allow the required starting torque of the motor to be maintained. Such starters (Fig. 27.35) provide *soft* starts (i.e., starts that minimize the mechanical stresses caused by rapid application of accelerating torque). Additional advantages of these units are reduced size and weight, long life, more sophisticated motor protection, and additional operating functions such as jogging and reversal. Disadvantages are higher cost and possible radio frequency noise problems.

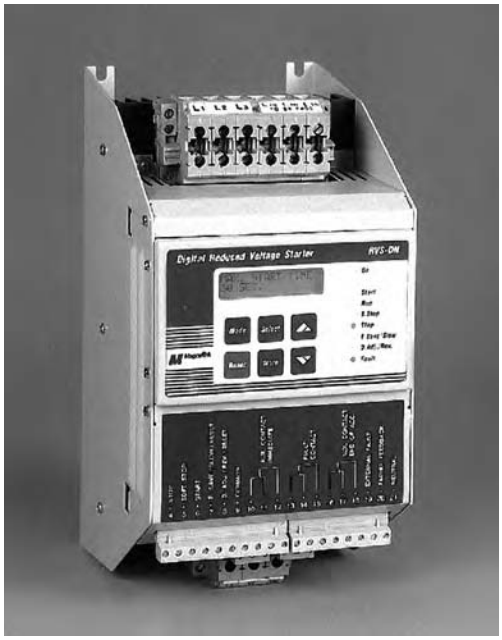


Fig. 27.35 *Soft starter type for 3-phase induction motors of up to 1400 hp (1045 kW), shown without an enclosure. This microprocessor-based unit provides two selectable starting characteristics with stepless acceleration, plus additional control and protection functions including reversing control, over- and undervoltage and current protection, and two normal motor operating speeds. (Photo courtesy of Magnetek.)*

(b) Motor Speed Control

Many applications in HVAC, fluid flow, and industrial systems require speed control of electric motors. Until recently, this constituted a problem whose solution was expensive, often space-consuming, and rarely energy-efficient. The reason for this is that the common squirrel-cage induction motor is essentially a constant-speed device, where speed is determined by power line frequency and motor design. Speed drops slightly (slips) as the load increases. Until the advent of cheap electronic power equipment, speed control was usually accomplished by using a wound-rotor motor in lieu of a squirrel-cage unit. This drastically increased both motor and controller costs while providing only limited speed control.

Advances in power electronics have made practical a variable-voltage, variable-frequency (VVVF) controller that gives smooth, continuous speed control over a range exceeding 30 to 1 while maintaining motor torque. These highly reliable controllers, also known as *variable frequency drives* (VFD), provide considerable energy economies that usually result in rapid payback of the relatively high first cost of equipment. The essentials of the VVVF control scheme are shown in Fig. 27.36. Voltage control, in addition to frequency control, is necessary in order to maintain a constant voltage/frequency ratio, which is necessary for efficient, safe

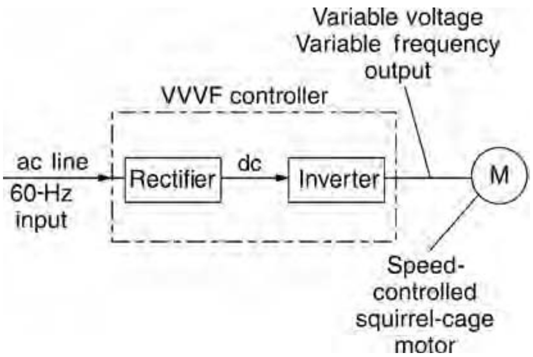


Fig. 27.36 *Schematic representation of the action of a variable-voltage, variable-frequency (VVVF) motor speed controller. Line voltage at 60 Hz is rectified to DC and the inverted voltage to AC. Frequency and voltage control are built into the inverters, designed to maintain a constant voltage-to-frequency ratio. This constancy is necessary to prevent malfunction of the motor as its speed is varied.*

operation. An increase in this ratio results in overheating of the motor, whereas a decrease results in insufficient torque. Additional advances in power electronics have produced motor speed controllers with controlled speed ratios approaching 1000:1.

One disadvantage of these speed controllers has been the production of line harmonics and radio noise of sufficient strength to constitute a serious engineering problem. At this writing, these problems have been mitigated, and will undoubtedly be pursued to the point that, except for highly sensitive areas, the interference will be negligible. At this point, however, the designer must investigate these effects for the particular application. Typical adjustable-frequency controllers are shown in Fig. 27.37.

27.27 MOTOR CONTROL EQUIPMENT

All the starters discussed previously are available in a wide range of sizes, voltages, and enclosure types. Every motor controller is required by the *NEC* to have a disconnecting means for safety reasons. Where convenient, this disconnect switch may be combined with the starter into a single unit known as a *combination starter*. A circuit breaker or fused switch is often used in such an arrangement, which then constitutes the branch circuit protection and disconnecting means (Fig. 27.38).

A typical, brief description of a conventional motor controller would be similar to the following: combination circuit-breaker type, across-the-line motor controller, NEMA size 2, three O.L. (overload) elements, 208 V, in a NEMA 1 enclosure; starter shall contain integral on/off pushbuttons.

Table 27.6 gives the approximate dimensions of one particular type of combination starter. As

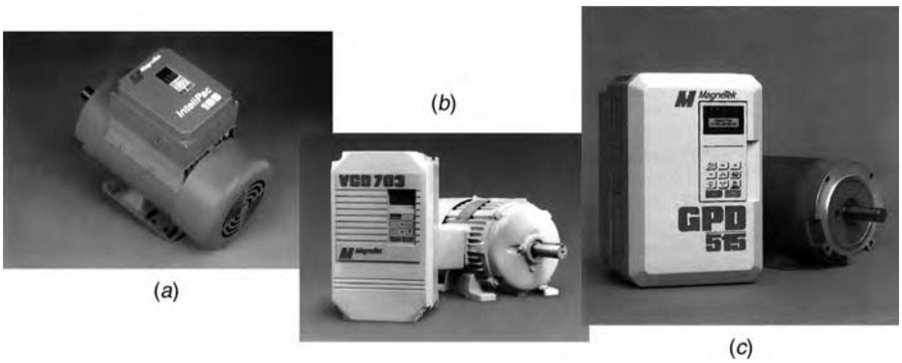


Fig. 27.37 *Three programmable, microprocessor-controlled motor controllers. (a) Integrated motor and controller for motors of up to 1 hp (0.75 kW). The controller provides a soft start, a speed control range of 40:1, high efficiency, multiple speed settings, and full motor protection. (b) Controller for motors of up to 3-phase, 400 hp (300 kW); this type of unit provides programmable functions including speed control from standstill to double-rated speed, reversing, adjustable acceleration, and full motor protection. (c) Controller that can be programmed for three different control modes. Speed control range, regulation, and torque curves vary in each mode to suit the specific controlled load. The controller has low harmonic distortion plus fault diagnostic software, in addition to the normal overload and protective characteristics. It also has terminals for remote monitoring and control plus network control capabilities. A 20-hp (15-kW), 230-V controller in a NEMA 1 (indoor) enclosure measures approximately 16 in. × 10 in. × 9 in. (400 × 250 × 230 mm) and weighs 24 lb (11 kg). (Photos courtesy of Magnetek.)*

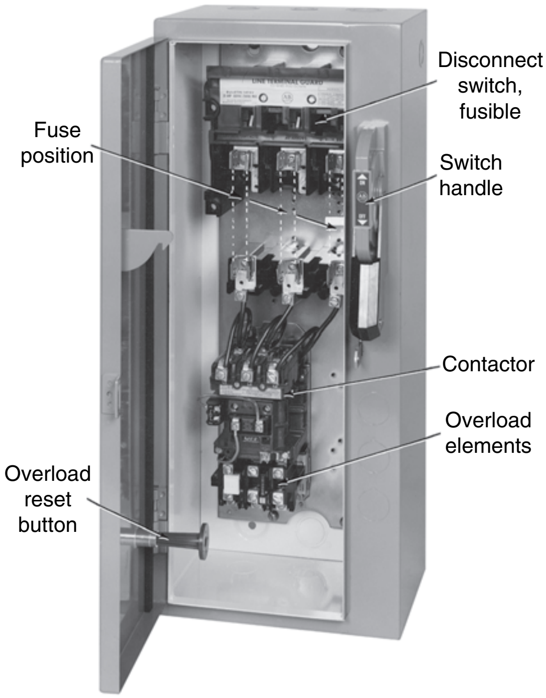


Fig. 27.38 *Interior of a conventional (non-solid-state) combination fused switch-type, across-the-line motor controller. Note that the unit is essentially a switch and a starter wired together and installed in a single cabinet. Approximate dimensions of the illustrated unit are 20 in. W × 48 in. H × 9 in. D (510 × 1140 × 230 mm), with a 75-hp (56-kW) capacity. (Courtesy of Allen-Bradley Co.)*

TABLE 27.6 Rating and Approximate Dimensions[a] of AC Full-Voltage Conventional Single-Speed Motor Controllers, 3-Phase Combination Circuit Breaker Type[b]

NEMA Size[c] Desig-nation	Maximum Horsepower (kW)[c]	Width	Height	Depth
			in. (mm)	
0	3 (2.2)	10 (254)	24 (610)	7 (178)
1	7½ (5.6)	10 (254)	24 (610)	7 (178)
2	15 (11.2)	10 (254)	24 (610)	7 (178)
3	30 (22)	20 (508)	24 (610)	9 (229)
4	50 (37)	20 (508)	48 (1219)	9 (229)
5	100 (75)	20 (508)	56 (1422)	11 (279)

[a]Dimensions vary among manufacturers.

[b]All starters are housed in a NEMA 1 indoor ventilated enclosure.

[c]Maximum hp (kW) that can be controlled at 208–230 V. When operating at 460 V, a starter one size smaller can *generally* be used.

with other electrical equipment, a current manufacturer's catalog must be consulted for reliable data on a particular manufacturer's products. Dimensions vary somewhat among manufacturers (while still meeting NEMA specifications). As noted previously, physical characteristics for control equipment of similar ratings can vary greatly among items made to meet IEC specifications and those made to NEMA specifications.

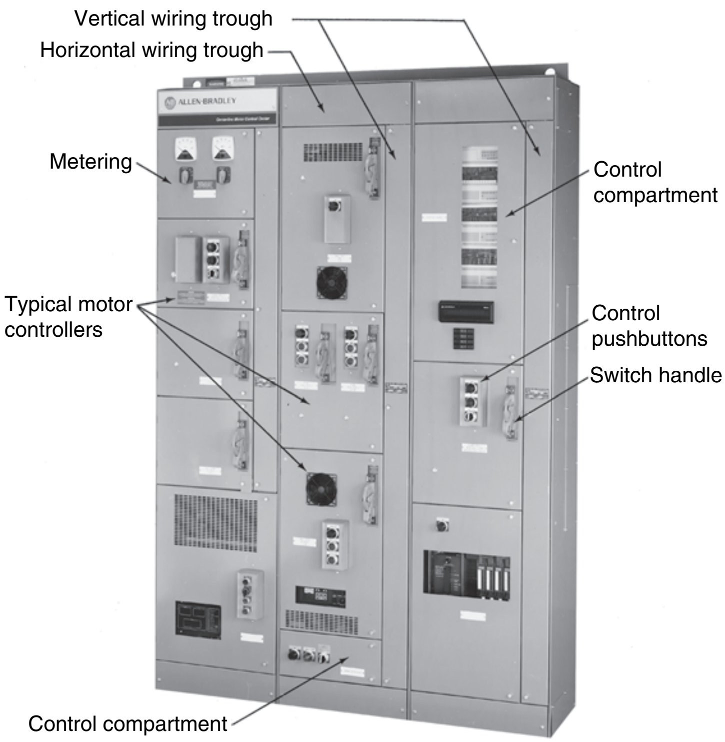
Where several motors are installed in close proximity to one another, it is often convenient from the control perspective, as well as economically, to combine the motor starters, disconnect switches, motor controls, and indicating devices into a single large assembly. Such an assembly is called a *motor control center* (MCC). Typical MCC types are shown in Fig. 27.39.

27.28 WIRING DEVICES: GENERAL DESCRIPTION

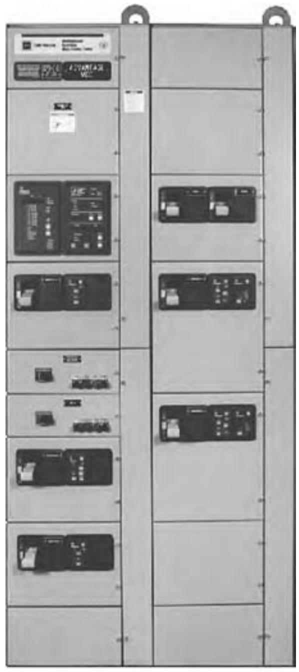
The general term *wiring devices* includes all devices that are normally installed in wall outlet boxes, including receptacles, switches, dimmers, fan controls, and so on. Attachment plugs, also called *caps*, and wall plates are also included in wiring devices.

There are three grades of device quality, using NEMA and UL grading nomenclature: hospital grade, federal specification grade, and UL general-purpose grade—in descending order of price and quality. Inasmuch as these grades correspond to published specification requirements, they are the only reliable gauge of construction quality. Hospital-grade devices are identified by a green dot on the device face. These devices are built to withstand severe abuse while maintaining reliable operation and must meet UL requirements for this grade.

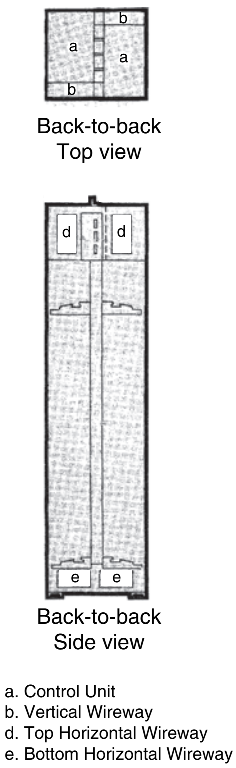
Manufacturers usually grade their devices as hospital grade, premium or industrial specification grade, commercial specification grade, and residential grade, in descending order of quality and price. Hospital grade is approximately the same among manufacturers because industry standards must be met. Industrial and commercial specification grades correspond roughly to federal specification grade, and residential grade to UL general-purpose grade. Manufacturers' grades are qualitative, although reputable makers list the NEMA and UL



(*a*)



(*d*)



(*b*)

(*c*)

Fig. 27.39 *Motor control centers (MCC) of various constructions. (a) Conventional MCC construction with magnetic motor starters, manual local control, analog metering, and conventional overload and protective equipment. (b) Back-to-back construction of conventional MCC adds only 5 in. (125 mm) to the basic 15-in. (380-mm) depth. (c) Units are 90 in. (2.3 m) high and 20 in. (500 mm) wide per section. Solid-state controllers can be installed in this unit, as well as in the MCC shown in (a), along with conventional magnetic contactors. (d) MCC that uses solid-state programmable controllers with heaterless overload protection. The unit also provides protection against phase loss, single phasing, and ground faults. Single side units in this construction are 90 in. (2.3 m) H × 20 in. (500 mm) W × 16–20 in. (400–500 mm) D (depending upon starter size). Back-to-back construction is 21 in. (534 mm) D. Photos courtesy of Allen-Bradley (a), Siemens-Furnas (b, c), and Cutler-Hammer (d).*

specifications that each of their grades meets. It is only on this standardized basis that a technical quality comparison can be made.

In application, industrial specification grade equipment is usually used in industrial and high-grade commercial construction; commercial specification grade in most educational and good residential buildings; and standard or residential grade in low-cost construction of all types. The grade of wiring devices should, as with all electrical equipment, be consistent with the quality of construction in the facility as a whole.

Although historically the term *wiring device* referred to devices that operate at line voltage (120, 208, 240, and 277 V) in a branch circuit, the term today also includes low-voltage lighting control devices, fan controls, and the like. The accepted criteria seem to be that only devices rated 30 amps or less, that can be mounted in a small wall box, are considered wiring devices. Communication attachments are not usually considered wiring devices, even when they are supplied by the electrical contractor. They are part of *premise wiring*, which is the term commonly used to describe data and communication system wiring, raceways, and devices (see Fig. 28.21).

27.29 WIRING DEVICES: RECEPTACLES

A receptacle is, by *NEC* definition, "a contact device installed at the outlet for the connection of a single attachment plug." This usually takes the form of the common wall outlet or, as illustrated later, larger and more complex devices. A comment about terminology is required. The common wall outlet is properly called a *convenience receptacle outlet*, *a receptacle outlet*, or a *convenience outlet*. The term *wall plug*, which is heard so often, is incorrect. A *plug* is another name for the attachment device (cap) on the wire that carries electricity to the appliance. The device at the end of the line cord is plugged into the wall, hence *plug*.

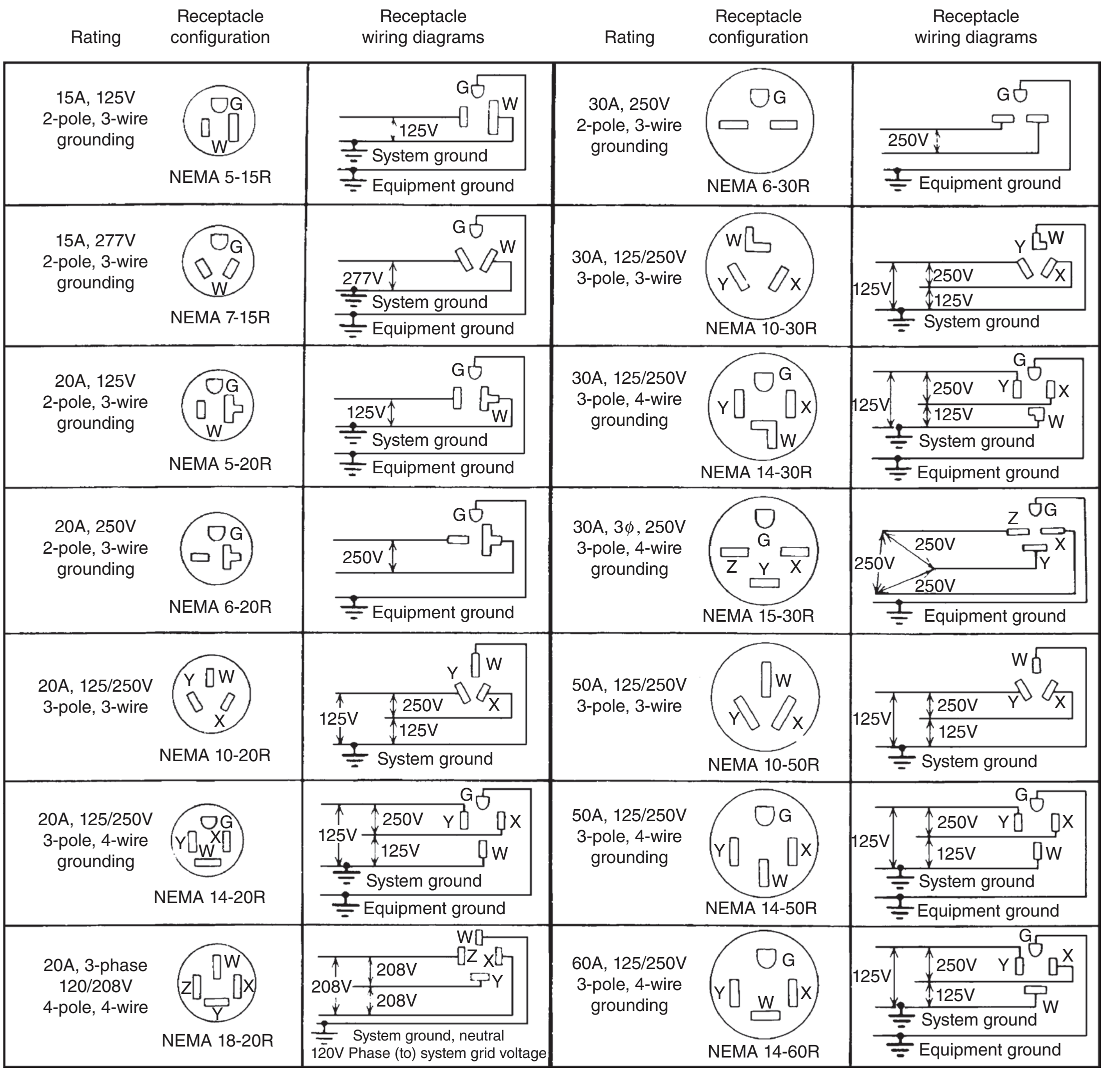
Because by *NEC* definition a receptacle is a contact device for the connection of a single attachment plug, and because the normal wall convenience receptacle will accept two attachment plugs, it is properly called a *duplex convenience receptacle* or *duplex convenience outlet*. Most people shorten this term to *duplex receptacle* or *duplex outlet*.

Receptacles are identified by the number of poles, the number of wires, and whether the device is designed for connection of a separate equipment ground. (This ground may connect to a separate equipment-grounding wire or to the metallic conduit system, according to system design.) The number of receptacle *poles* equals the number of current-carrying contacts, including the neutral. The equipment ground connection (pole) is not counted because it does not (normally) carry current. The number of *wires* includes the equipment ground connection because it is wired. The equipment ground connection (grounding pole) should not be confused with the system ground (usually the neutral pole), nor may the wiring for the two be interchanged (see Section 29.4).

In a typical application, a receptacle for an electric dryer with a 4800-W, 208-V heating element and a 1/6-hp (0.12 kW), 115-V motor would be NEMA 14-50R (Fig. 27.40). The motor would connect across W and X, the heater across X and Y, and the appliance case to G. Receptacles installed on standard 15- or 20-A branch circuits must be of the grounding type. Receptacles connected to different voltages, frequencies, or current type (AC or DC) on the same premises must be polarized so that attachment plugs are not interchangeable. Figure 27.40 shows some of the standard receptacle configurations and their ratings. Figure 27.41 shows typical receptacle construction plus enclosures for use in damp and wet locations.

Receptacles are readily available from 10 to 400 A, 2 to 4 poles, and 125 to 600 V. In addition, special types such as locking, explosion-proof, tamperproof, and decorative design units are made. Also, specific-usage devices, such as electric range receptacles, are available. All receptacles other than the normal 15/20-A, 3-wire, parallel-slot type should be specified to be furnished with at least two matching caps (plugs). A typical receptacle specification would be: receptacle, duplex, 2-pole, 3-wire, grounding type, 20 A, 250 V, federal specification grade, for indoor use. Receptacles are normally mounted vertically between 12 and 18 in. (305–457 mm) above the finished floor (AFF), except that in shops, labs, and other areas where tables are placed against the walls, 42 in. (1.07 m) is the usual mounting height.

In addition to these types, several manufacturers produce a receptacle with built-in ground-fault



Note: "W" denotes white system ground or neutral
"G" denotes green equipment ground.

Fig. 27.40 *Receptacle configuration chart with selected common general-purpose, nonlocking devices with associated NEMA designations.*

circuit protection (Fig. 27.42). For a discussion of these ground-fault circuit interrupter (GFCI) receptacles, see Section 29.4.

The sensitivity of certain modern electronic equipment to voltage surges and electrical *noise* (random, spurious electrical voltages) has led to the development of two special receptacles. Receptacles with built-in surge suppression protect connected equipment from overvoltage spikes. Receptacles with an insulated equipment-grounding terminal separate the device ground terminal from the system (raceway) ground because it has been determined that much unwanted electrical noise can be eliminated by such disconnection. The receptacle's insulated ground terminal is connected to an isolated green ground conductor that carries through the entire system but is connected to the system ground at the service entrance only; hence the

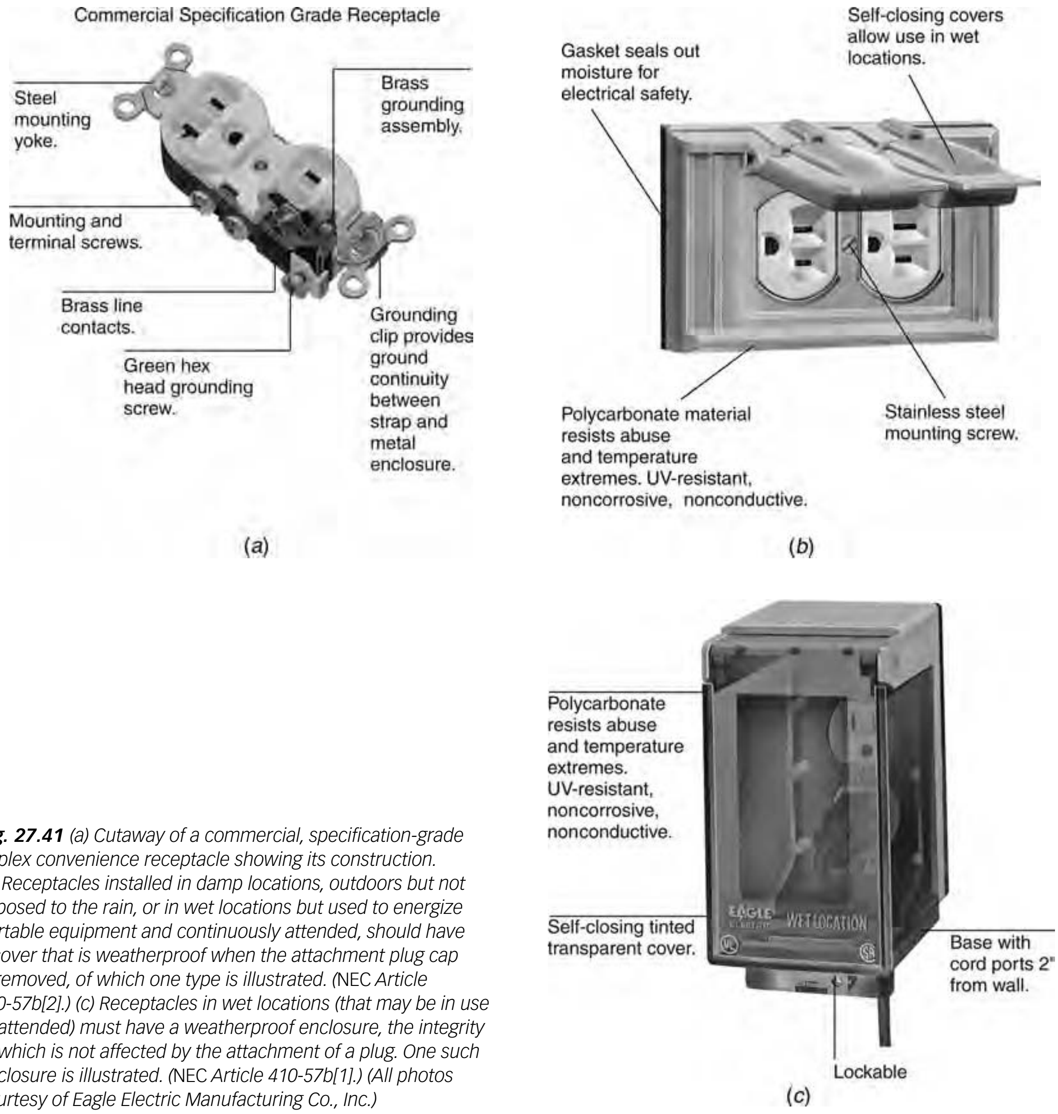


Fig. 27.41 *(a) Cutaway of a commercial, specification-grade duplex convenience receptacle showing its construction. (b) Receptacles installed in damp locations, outdoors but not exposed to the rain, or in wet locations but used to energize portable equipment and continuously attended, should have a cover that is weatherproof when the attachment plug cap is removed, of which one type is illustrated. (*NEC *Article 410-57b[2].) (c) Receptacles in wet locations (that may be in use unattended) must have a weatherproof enclosure, the integrity of which is not affected by the attachment of a plug. One such enclosure is illustrated. (*NEC *Article 410-57b[1].) (All photos courtesy of Eagle Electric Manufacturing Co., Inc.)*

name *isolated ground*. Isolated ground receptacles are identified by an orange triangle on their face (see Fig. 27.43). A receptacle with built-in surge suppression is shown in Fig. 27.43.

27.30 WIRING DEVICES: SWITCHES

Switches of up to 30 A that can be outlet-box mounted fall into this category. Generally, because of their better construction, AC-only switches are preferable to the AC/DC type. The usual AC switch rating is 15, 20, or 30 A at 120 or 120/277 V. Usual constructions are single-pole, 2-pole, 3-way, 4-way, momentary-contact, 2-circuit, and maintained-contact SPDT (single-pole, double-throw) and DPDT (double-pole, double-throw). Operating handles are toggle, key, push, touch, rocker, rotary, and tap-plate types. Mercury and AC quiet types are relatively noiseless; toggle, tumbler, and AC/DC types are generally not. A typical switch specification might be: switch, single-pole, AC, quiet type, federal specification grade, 15 A, 120 V, with press handles lighted when off, for side wiring only.

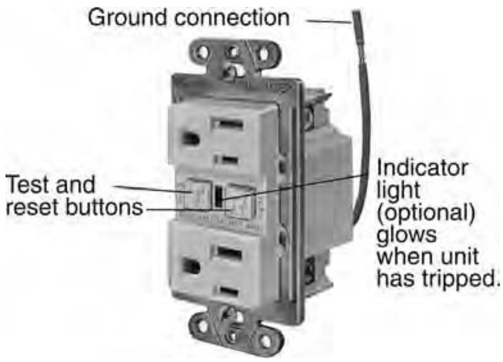


Fig. 27.42 *Where it is desired to provide ground-fault protection at a single outlet only, and thereby localize power interruption (rather than using a GFCI circuit breaker on the entire circuit), a receptacle containing a ground-fault interrupter, as illustrated, may be used. A test button is provided to permit periodic testing, and a reset button reenergizes the receptacle after it has tripped on ground fault and the fault has been cleared. (Courtesy of Eagle Electric Manufacturing Co., Inc.)*

Fig. 27.43 *Hospital-grade, insulated (isolated) ground receptacle used where heavy duty is expected, and both reliability and freedom from electronic noise are required. Hospital grade is denoted by a green dot on the upper left of the receptacle face, and the insulated ground by an orange triangle on the upper right. (Some manufacturers make the entire receptacle orange.) (Photo courtesy of Leviton Manufacturing Co.)*

A switch incorporating a solid-state rectifier is readily available that gives high/off/low control for *incandescent lamps* and costs very little more than an ordinary switch. Typical applications are in areas where a lower illumination level is often acceptable and always desirable as an energy-conserving measure. In high-security areas where an easily defeated normal key-operated switch is inadequate, a tumbler lock-controlled unit can be used. Loads that can be timed out, such as bathroom heaters and ventilating fans, can be controlled by a spring-wound timer switch, as illustrated in Fig. 27.44 (which also illustrates a few common switch types). Figure 27.45 shows two common switch designs in cutaway, revealing their construction and operating mechanisms. A solid-state switch with adjustable time delay is shown in Fig. 27.46.

Thanks to miniature electronics, a programmable switch is available that fits into a wall-outlet box in lieu of an ordinary switch. The unit acts as a solid-state 15-A switch and can be readily

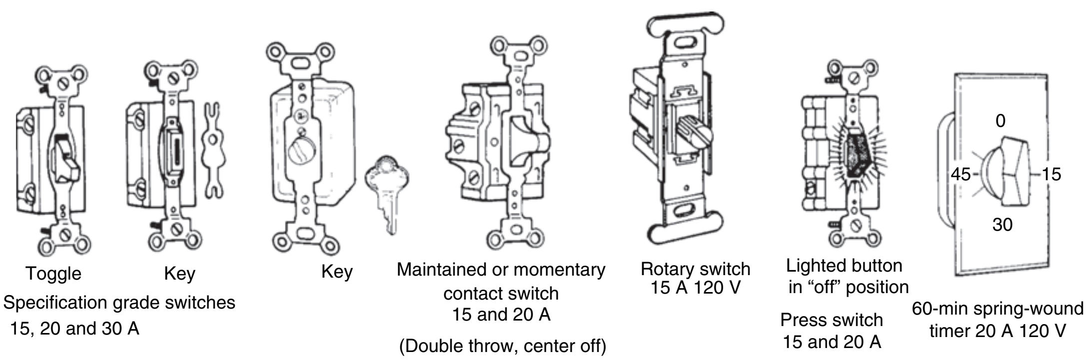


Fig. 27.44 *A few of the most common wiring device switches, generally installed in a small wall box and used for control of lighting circuits.*

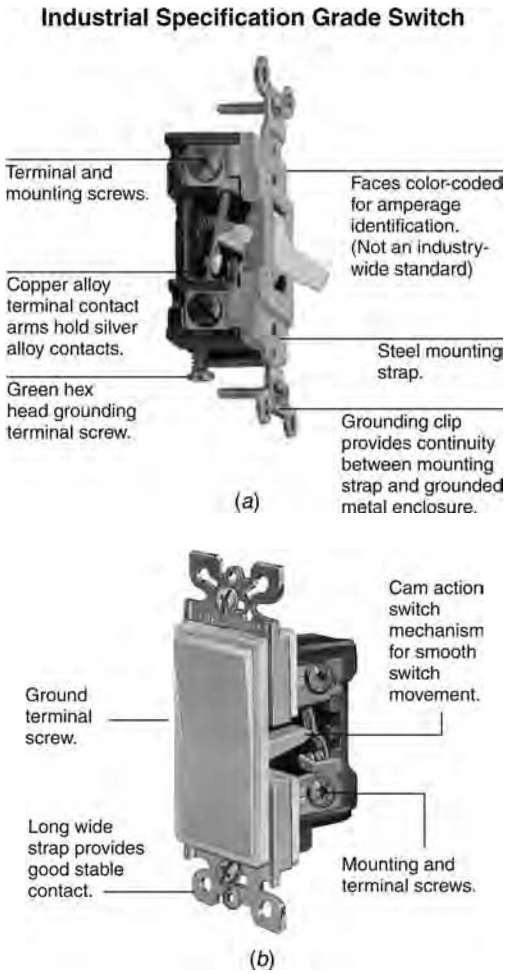


Fig. 27.45 *Cutaway drawing of two common wall-switch designs showing operating mechanisms and construction details. (a) Conventional toggle design. (b) Rocker plate design. (Drawings courtesy of Eagle Electric Manufacturing Co.)*

Fig. 27.46 *Solid-state adjustable electronic switch timer that mounts in a common wall-switch box. The unit switches off, with delay adjustable from zero to 15 minutes in five discrete steps. Units such as these can control incandescent and fluorescent lamps and small motors. They are applicable where either direct manual control or occupancy sensors are inapplicable. (Photo courtesy of Leviton Manufacturing Co.)*

programmed to switch the controlled circuit or device at preset times (see Fig. 27.46).

27.31 WIRING DEVICES: SPECIALTIES

The most common device in this group, which also includes pilot lights, fan controls, and other small motor controls, is the lighting dimmer. The original lighting dimmers were variable autotransformers. They were large, heavy, and expensive, and therefore found application mainly in theater lighting, displays, and the like. The advent of small electronic units (silicon-controlled rectifiers, SCRs) made the modern wall-box dimmer possible. The simplest units are rotary, with limited capacity and applicable only to incandescent lamp loads. One of their disadvantages, still found in inexpensive units, is the production of annoying radio frequency interference (RFI) and line harmonics. Newer models are available that provide preset control, combine dimming and switching, are usable for smooth fan speed control, can be remotely controlled (in addition to local control), provide automatic fadeout, and can dim fluorescent lamps (provided with dimming ballasts). A few types are shown in Figs. 27.47 and 27.48.

27.32 LOW-VOLTAGE SWITCHING

The switches illustrated and discussed in Section 27.30 are all full-voltage types; that is, they are wired directly into the load circuit and operate at line voltage and full current. A control scheme

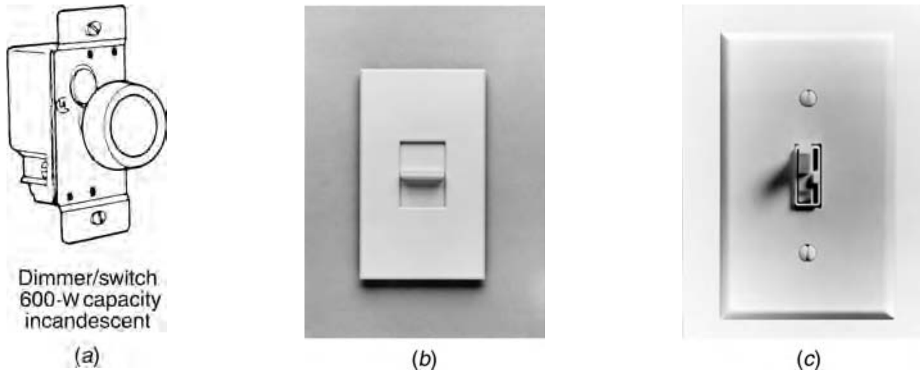


Fig. 27.47 *(a) Simple solid-state dimmer, suitable for a maximum 600-W incandescent load only. The switch permits level preset in a pushbutton design. Inexpensive units may cause considerable radio frequency interference (RFI). (b) Slide dimmer for a 600-W incandescent load, including on/off and level preset. This dimmer is available with a wireless receiver that responds to a handheld infrared remote control. (c) Combined on/off switch and slide dimmer provides preset level control. Units similar to (b) and (c) are available for loads of up to 1000 W, fluorescent lamp control (with appropriate ballast), and fan speed control. (Photos b and c courtesy of Lutron Electronics Co., Inc.)*

that uses light-duty, low-voltage (24-V) switches to control line voltage relays, which in turn do the actual circuit switching, is illustrated in Figs. 27.49 and 27.50. The system is variously referred to as *low-voltage switching*, *remote-control switching*, and *low-voltage control*.

Because the loads in this system are relay controlled, any number of switches and control devices can be wired in parallel to operate a relay and thereby effect the switching. Thus, the control can be local, remote, and master, with individual override by local control devices such as occupancy sensors, and central control or override at a central controller by timers, daylight controllers, and so on. The advantages of this system of control over full-voltage switching are:

- Flexibility of control location
- Individual load control override by local control devices (occupancy sensors, photocells)
- Group load override by central control devices such as timers, daylight controllers, and energy management systems
- Low cost of low-voltage, low-current wiring compared to full-voltage wire and conduit

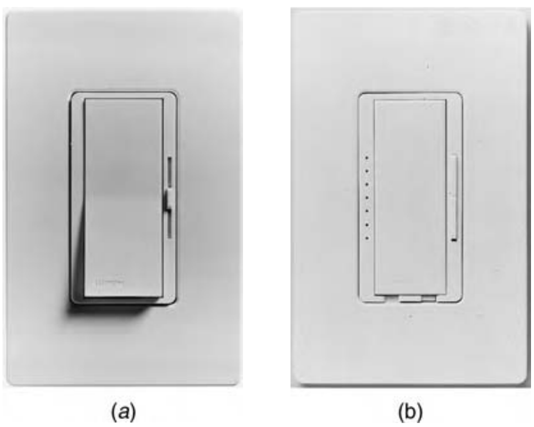


Fig. 27.48 *(a) Combined tap switch and slide dimmer provides preset level control. A built-in night-light suggests a residential application. (b) Multifunction tap switch in the center permits switching to full brightness, gradual brightening to preset, 10-second fade-out, and off. Rocker switch at the right controls levels. LEDs behind pinholes at the left provide an indication of the preset level. Both illustrated unit designs are available for incandescent and fluorescent (with special ballast) lamp control and fan speed control. Both are designed with RFI suppression. (Photos courtesy of Lutron Electronics Co., Inc.)*

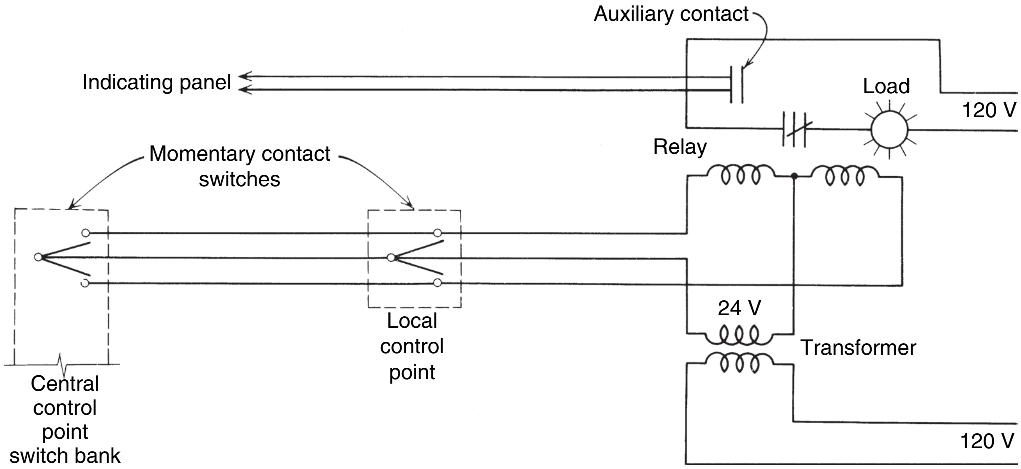


Fig. 27.49 Low-voltage switching control. Multipoint control and central control are illustrated. The diagram shows the relays located at the load. Central relay cabinets are used in dense load areas.

- Inherent system flexibility and simplification of alterations
- Monitoring of the status of individual loads at a centralized control panel by the use of relays with auxiliary contacts (see Fig. 27.49)

The second and third points are particularly important from an energy conservation perspective, as it has been amply demonstrated that reliance on manual controls to limit energy usage yields disappointing results.

The basic components of the entire system are the control relay and the switches, shown in Fig. 27.51. Small systems use hard wiring (physically wired connections), with the hard-wired relays installed either dispersed at each controlled fixture (or lighting group) or grouped in a relay panel. When the number of relays exceeds about

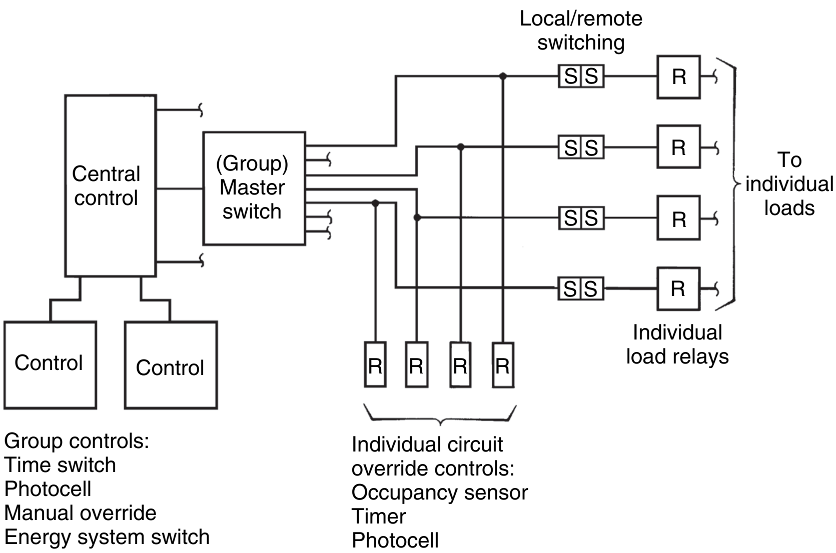
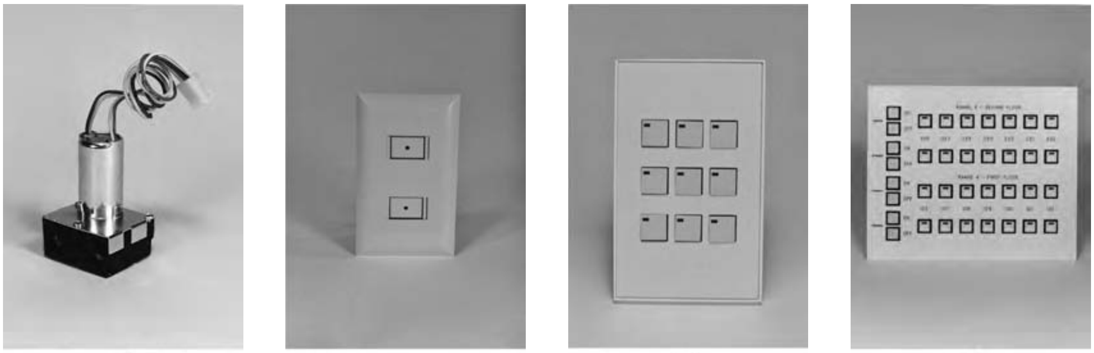


Fig. 27.50 Schematic arrangement of a large low-voltage switching system. Individual loads can be switch-controlled from multiple locations, including a group (master) control point. In addition, local control devices such as photocells and occupancy sensors can override the local switches to maximize energy conservation. Central (group) control devices can perform the same override function at the group level.



(a) (b) (c) (d)

Fig. 27.51 *Components of low-voltage switching and control systems for lighting and other electric loads. (a) The basic switching device is a single-pole, double-throw latching relay with a 24-V coil and 20-A, 120–277-V contacts. It is shown with a plug-in connector on its leads, making it suitable for rapid mounting in a relay panel (see Fig. 27.52). The same relay without the connector is suitable for hard-wiring at a controlled device. (b) Low-voltage (24-V) wall switches can be mounted singly or ganged in groups of two to eight switches. Switches are available in button, rocker, key-operated, and lighted designs (as in b–d). (c) Switching station with pushbutton low-voltage switches, each with an LED to indicate switch position (on/off). (d) Switch bank with illuminated pushbutton switches identified with room number and floor. The on/off switches at the left of the bank are override switches for the corresponding horizontal line. (Photos courtesy of Touchplate Technologies, Inc.)*

20, these panels become so densely wired that control changes become difficult and tedious. As a result, prewired computer- or microprocessor-controlled panels are used in large systems, where connections can be made and changed easily. The interior of one such panel is shown in Fig. 27.52. The logic of a medium-sized computer-controlled system is shown in Fig. 27.53. Manufacturers have made software available that permits rapid, accurate design of complex, large systems. A typical computer screen in such a system is shown in Fig. 27.54.

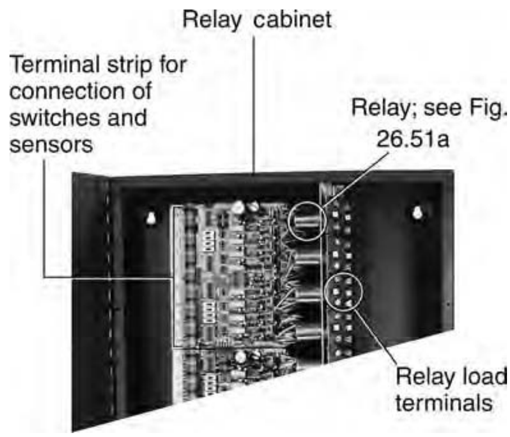


Fig. 27.52 *Prewired relay cabinet (partial). Field wiring consists of control wiring to switches and sensors and power wiring to the controlled loads. (Photo courtesy of Touchplate Technologies, Inc.)*

27.33 WIRELESS SWITCHING AND CONTROL

Full-voltage local switching was described in Section 27.30, and low-voltage switching, both local and remote, was described in Section 27.32. The next logical step is remote wireless control and switching. These systems have undergone extensive development. They impinge on the design considerations of architects and building engineers to the extent that facilities to accommodate such systems must be provided if such controls are to be used on a project.

Aspects of wireless control and switching, as well as system functioning and application to lighting control, are discussed in detail in Chapter 16.

27.34 POWER LINE CARRIER SYSTEMS

Although the advantages inherent in flexible, programmable load-switching systems such as those described in the preceding sections are undeniable,

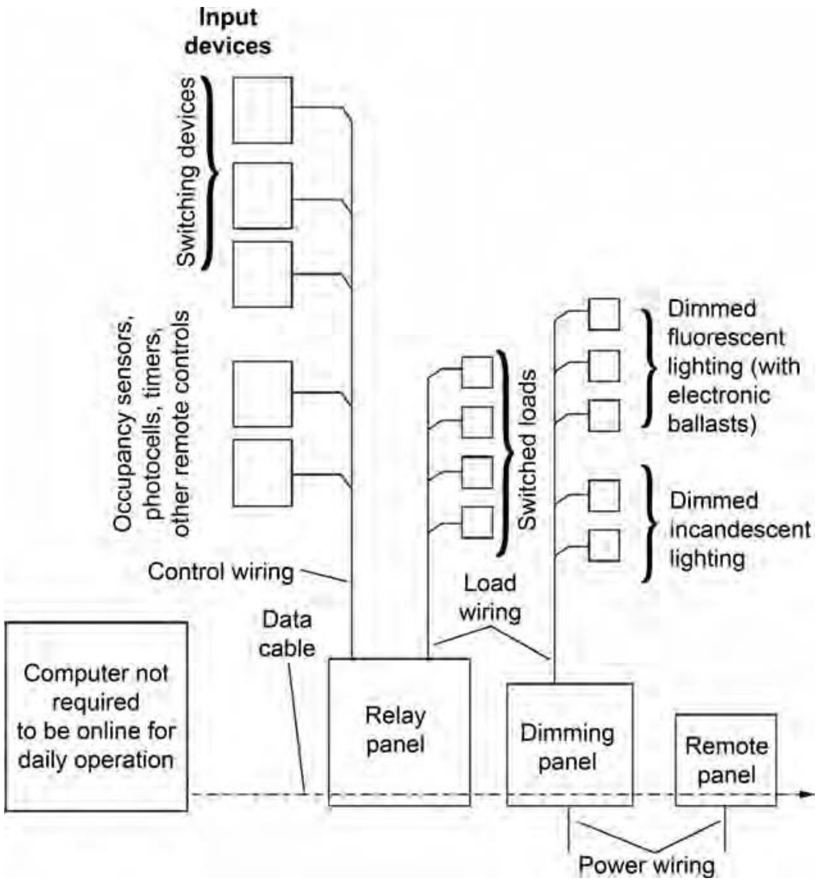


Fig. 27.53 *Block diagram of a large, computer-controlled, low-voltage control system. The relay panel contains the incoming and outgoing power and control wiring, the switching relays, and the computer interface card. The system arrangement is controlled by computer software. (Courtesy of Touchplate Technologies, Inc.)*

particularly in connection with energy management systems, their high first cost frequently makes their use uneconomical. This is particularly true when retrofitting large, complex facilities with energy management controls, where the cost of wiring, even when using low-voltage control wires, can amount to more than half of the total cost of the project.

To minimize control wiring costs, a system of control signal transmission that uses the electric power wiring (either new or existing) to conduct signals was developed, thus removing the need and expense for dedicated control wiring. This system is called a *power line carrier* (PLC) system because the power line carries the control signal. An ancillary benefit of such an arrangement is that not only can it be added to an existing system, it can also be easily removed, thus making possible and economical the leasing of energy management control systems.

The system operates by injecting into the power wiring a series of low-voltage, high-frequency, binary-coded control signals, which then disperse over the entire power network. Only a receiver that is “tuned” to receive a particular code reacts, generally by operating a local device, which in turn connects, disconnects, dims, or brightens a particular load. In practice, the control signal generator can be a small, manually programmed controller, as in a residence, or a computer-operated energy management or lighting controller in a commercial facility. The receivers are normally of four types, most of

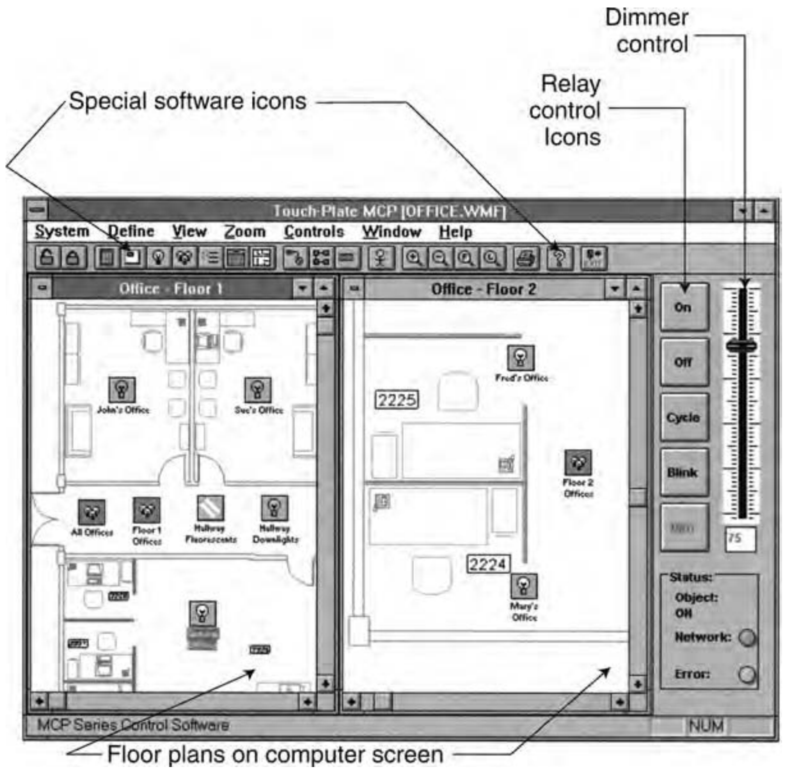


Fig. 27.54 *Typical computer screen of low-voltage control software showing facility floor plans (scanned in) and controlled loads. The icons at the top of the screen are customized and are used to control relays, make connections, check status, print, and log events by time and date. Other screens enable group and event definition, labeling, establishment of priorities, and other global sequential and individual control functions. (Courtesy of Touchplate Technologies, Inc.)*

which are designed to fit into an ordinary wiring device box:

1. A wall-switch module, which acts as a normal manual wall light switch but also contains a coded receiver and a fully rated relay (20 A, 125 V or 277 V)
2. A wall receptacle module, which contains a 20-A receptacle along with a receiver and relay that serve to switch power on and off
3. A switching module, which can be connected to activate contactors, small motors, and the like
4. A dimming module, which provides both local and remote control

Some of these components are shown in Fig. 27.55. Larger, multiple-circuit switching modules are also available for more extensive systems. Each miniature receiver can be manually tuned in the field (i.e., its code can be set and reset readily), giving the entire system extreme flexibility.

The system operates in the same manner as a low-voltage switching system or an energy management or lighting control system, with the essential difference that no dedicated control wiring is required. In retrofit jobs, existing wall switches and receptacle outlets are replaced with receiver-controlled units; in new installations, these devices are installed initially.

Because the control signals travel over the power wiring and are therefore attenuated by high-resistance connections, poor grounds, and faulty wire insulation, PLC installations require a high-quality power wiring installation to operate properly. In retrofit work, preliminary tests occasionally indicate the impracticability of a PLC installation because of the condition of the power wiring system. Another problem encountered in PLC systems

Fig. 27.55 *Components of a residential-type PLC system. (a) Control unit, at which both manual and automatic (programmed) control of a maximum of 256 address codes is possible. (b) Wall-switch module has local dimming and switching functions in addition to being remotely controlled from the control center (a). (c) Duplex wall receptacle, either split-wired with local programming of one-half of the outlet or complete remote control. (d) Outlet box wall-mounted control switch that provides local group control (switching and/or dimming) for one to four devices (address codes). (Photo courtesy of Leviton Manufacturing Co.)*

is interference with the PLC control signals from radio noise generated by faulty power equipment and by improperly shielded or grounded electronic equipment. These problems can frequently be overcome by careful testing, installation of filters and jumpers, and repair of improperly operating equipment. In addition to energy management and normal lighting control, PLC control can be applied to group switching of other loads, such as office machines, in addition to simplifying control of temporary light and power for special events.

27.35 POWER CONDITIONING

(a) General Information

Power conditioning is a term that describes the process of converting utility-supplied electrical power, which is frequently characterized by transient surges, spikes, radio frequency noise, and voltage fluctuation, to a pure (noiseless), accurately voltage-regulated sinusoidal waveform, normally referred to as *computer-grade power*.

Some form of power conditioning is required by all large-scale data-processing and telecommunication equipment and by many other types of electronic equipment. This is due to their extreme sensitivity to fluctuations in the power supply voltage and particularly to random high-frequency voltages superimposed on the power supply voltage, known as *radio frequency interference* (RFI) or simply *radio noise*. In the case of data-processing equipment (computers and peripherals), radio noise can cause data errors; slow voltage fluctuations can cause overheating, data loss, and premature equipment failures; and large, rapid voltage fluctuations (spikes, transients) can cause equipment burnout and system collapse. The economic ramifications of such effects on large commercial data-handling systems are so severe that power conditioning has become almost universal. (Power conditioners must not be confused with uninterruptible power supplies [UPS], which function to maintain power during utility *failure*, although in many commercial installations, both functions are served by a single equipment package.)

(b) Source of Disturbance

Utility power systems are designed to maintain voltage and frequency within certain limits on an average, long-term basis. For valid technical reasons, utility equipment cannot react to the short-time disturbances that are so inimical to electronic equipment. Furthermore, much of the noise in utility lines is introduced by users and is therefore beyond the utility's point of control. Disturbances on the electrical power line can generally be classified into three types: voltage variations, electrical noise, and transients.

1. *Voltage variations.* These can be caused by short-time current drain, such as during motor starts, deliberate voltage reductions (brownouts), load switching of EMS systems, excessive line voltage drop due to heavy loading or current leakage, and similar problems. These variations are *relatively* slow and long-lasting.
2. *Electrical noise.* This is a low-amplitude, higher-frequency voltage that, when superimposed on the power line, results in a distorted waveform.

Sources of such extraneous voltages are electronic equipment power supplies, lighting dimmers, solid-state motor controls, PLC systems, arc welding, switching transients caused by branch circuit switches and relays, and voltages induced by local magnetic fields.

3. *Transients.* These are large, short-duration voltage variations, also known as *surges* or *spikes*. They are the principal culprits in major equipment failures. They are caused by lightning strikes to overhead lines (possibly many miles from an affected installation), by electrical system faults, and by utility switching of high-voltage lines, transformers, capacitor banks, generators, and circuit reclosers.

27.36 POWER-CONDITIONING EQUIPMENT

Each of the three types of problems described in the preceding section requires its own type of correction. Voltage variations are corrected with voltage regulators; noise problems are corrected by electrical isolation, filtering, and noise suppression; and transients are treated with surge suppressors. Each corrective device is a separate entity that can be applied individually to suit the particular problem encountered or in combination with another conditioning device. The choice in a specific installation is a highly technical decision and should be made by the facility's electrical engineer after careful analysis of the quality of the utility service. A few general recommendations can be made.

1. All computer installations, including the smallest, should be protected from line transients with an appropriate surge suppressor. Multitap plug-in strips (low-cost) with integral surge suppressors are unsatisfactory unless they have surge current, clamping voltage, and surge-energy specifications, and these meet the installation requirements.
2. Major data-processing installations normally require all three types of line treatment. The most economical way to provide them is with a single integrated power-conditioning unit.
3. Considerable improvement in the quality of electrical power can frequently be achieved by the simple expedient of running separate electrical feeders for sensitive loads.
4. Physical isolation of sensitive equipment areas is frequently helpful, particularly when disturbances are being induced by proximity to switching, arcing, and rectifying equipment. Discharge-type lighting, including fluorescent, mercury, sodium-vapor, and metal–halide, can cause interference, especially when used with electronic ballasts.
5. It was found some years ago that much of the noise in electrical power systems was introduced through the (equipment) grounding pole of an electrical receptacle. Because this connection is required for electrical safety, it cannot be eliminated. It can, however, be separated from the wiring system ground and still maintain its function. Receptacles so constructed are color-coded either entirely orange or have an orange triangle on the face (see Section 27.29). This "fix" is particularly effective where electronic dimmers, ballasts, and switching devices are present. Because the insulated ground receptacle (sometimes referred to as an *isolated* ground receptacle) is a special item, it must be clearly indicated in the contract documents (drawings and specifications). Furthermore, because these receptacles require special isolated wiring, the entire matter must be studied carefully during the electrical design stage and before issuance of construction contracts.
6. A problem related to equipment that produces radio noise is that this same equipment also produces harmonics that appear on the system neutral and can cause overloading. This subject is covered in Section 29.18.

The issue of power quality is so important in modern commercial installations that the following steps should be taken essentially as a matter of course during design:

- A detailed report should be obtained from the electric utility that will be supplying electric power, showing power outages, voltage constancy, frequency control, and, if possible, oscillograms of waveforms at random intervals over the past year. Particularly important are periods of peak loading and periods of weather extremes.
- A power-quality study should be made in the area in which the facility will be (or is) located. Sophisticated instrumentation for this purpose as well as specialists in this field are readily available.

- An in-depth study of all of the electrical equipment to be used in the building should be made for the purpose of:
  - Reducing the sources of electrical disturbances.
  - Determining the tolerance or sensitivity of the data-processing equipment to be used. In the absence of reliable data for the second purpose, as is the case in speculative construction, a high degree of sensitivity should be assumed. In any case, for equipment that is known to produce radio noise, such as electronic lighting ballasts and dimmers, the specifications should include limitations plus a requirement for submission of laboratory tests on random samples.
- Power companies may offer "computer-grade power" that meets stated limitations to voltage fluctuation and the like. This type of service is desirable for all new office space or full building renovations. For individual office spaces, separate power-conditioning equipment is required.

Table 27.7 and Fig. 27.56 give some idea of the physical characteristics of power-conditioning

Fig. 27.56 *This single-phase power conditioner supplies noise filtering and surge suppression by use of an isolation transformer, ground noise filters, and category A and B surge suppression (see Section 27.37c). It is rated 5 A, 120 V, measures 6 in. H × 7 in. W × 11 in. D (150 × 180 × 280 mm), and weighs 18 lb (8 kg). A similar unit rated 20 A, 120 V measures 8 in. H × 8½ in. W × 14 in. D (200 × 215 × 355 mm). (Photo courtesy of Leviton Manufacturing Co.)*

TABLE 27.7 Power-Conditioning Equipment

Equipment Functions				Dimensions in. (mm)		
Voltage Regulation	**Noise Suppression**	**Surge Suppression**	**kVA[a]**	**H**	**W**	**D**
x			5	15 (381)	20 (508)	20 (508)
			10	35 (889)	40 (1016)	20 (508)
			20	40 (1016)	40 (1016)	30 (762)
x	x		0.25	6 (152)	6 (152)	10 (254)
			0.5	7 (178)	7 (178)	12 (305)
			1.0	8 (203)	10 (254)	15 (381)
			3.0	10 (254)	12 (305)	20 (508)
x	x		5	10 (254)	10 (254)	15 (381)
			10	20 (508)	30 (762)	15 (381)
			20	30 (762)	30 (762)	20 (508)
x	x	x	5	40 (1016)	30 (762)	30 (762)
			10	50 (1270)	35 (889)	30 (762)
			20	70 (1778)	40 (1016)	35 (889)
		x	NA[a]			
			15 A	3 (76)	3 (76)	16 (406)
			100 A	10 (254)	12 (305)	12 (305)
			500 A	15 (381)	15 (381)	12 (305)

[a]Surge suppressors are rated by transient energy-handling capability, and therefore a kVA rating is not applicable. However, because transient energy increases with the kVA size of protected equipment, a service ampere rating is given.

equipment. Dimensions are typical and are indicative only of equipment bulk. Designs vary widely among manufacturers, as do, therefore, individual dimensions. Voltage-regulating equipment containing regulating transformers is very heavy, and this must be considered during design. Power-conditioning equipment is frequently combined with UPS equipment (see Section 27.38).

27.37 SURGE SUPPRESSION

The full term for this aspect of power conditioning is *transient voltage surge suppression* (TVSS). Because transient voltages, also called *surges* or *spikes*, can cause major physical damage to computer systems and other types of electronic equipment, it is this aspect of system protection that has generally received the most attention (including a fair amount of highly imaginative advertising). Surge suppressors are available in a wide variety of designs and ratings, ranging from the ubiquitous cord-connected, multiple-outlet strip to large, 3-phase, service-entrance units. They all have a single purpose, however: to suppress (limit) a voltage surge to a level that the protected equipment can withstand without damage. This is done in two ways:

1. By placing one or more devices that present a high impedance in series with the incoming voltage transient, thereby limiting the let-through current.
2. By placing one or more devices across the incoming power line, in parallel with the protected load, that present a low impedance to the high transient voltage and thereby bypass (shunt away) the incoming disturbance's current. Many TVSS units use both of these techniques in a single "hybrid" unit.

(a) Terminology

To be able to select TVSS units and compare their ratings, a basic technical vocabulary is necessary.

Avalanche diode. A solid-state device placed in parallel with a protected load. It responds to overvoltage in nanoseconds by conducting (i.e., placing) its very low impedance across the incoming voltage. This results in a large ("avalanche") bypass current flow that serves to reduce the incoming voltage. It has a low clamping voltage (definition follows) and low energy absorption capacity. This latter characteristic causes "wear" and eventual failure.

Clamping voltage. The voltage at which a shunting device (such as an avalanche diode) begins to conduct (and thereby clamp) an incoming voltage surge. The lower a device's clamping voltage, the better its suppression action.

EMI/RFI rejection. A measure of the attenuation, by a TVSS device, of electromagnetic interference (EMI) and RFI. A TVSS device, due to its internal filters, always provides some radio noise attenuation. This characteristic is not of primary significance to selection of a device used primarily for surge suppression.

Gas tube surge protector. A high-energy shunt device, typically found in high-capacity, good-quality TVSS units that are subject to large surges (such as those caused by lightning). It consists of a gas-filled tube with two electrodes. The tube conducts when a high-voltage surge causes its electrodes to arc over. Because of low arc impedance, the current drain and energy absorption are very high, thus clamping the incoming surge. Its principal drawback is its relatively slow response, which necessitates its use in conjunction with other, faster devices.

Isolation transformer. A transformer with two separate windings and no conductive electrical connection between them. By virtue of the inductive coupling of the windings, considerable attenuation of sharp voltage spikes is achieved. It can be used in high-capacity TVSS units in lieu of multiple solid-state components in parallel. It is also useful in attenuating high-frequency noise at any voltage level.

Joule rating. A *joule*, equal to 1 watt-second, is the SI unit of energy. A device's joule rating is a measure of its capacity to absorb and dissipate heat generated by its action. Although the joule rating is important where large amounts of energy are to be absorbed, as in (hard-wired) units at a service entrance or at a power distribution point, published ratings can be misleading because there is, at this writing, no industry-wide standard calculation procedure for joule rating. As a result, the industry standard specification form (NEMA LS 1) for TVSS devices does not include this rating.

Maximum surge current. A measure of a device's ability to divert and dissipate surge current without failing. It is a useful metric for TVSS devices used at service entrances and, for reasons explained previously, is more reliable than published joule ratings.

Metal-oxide variable resistor (MOV). A shunt device somewhat slower than an avalanche diode but with much higher energy absorption capability and higher clamping voltage. MOVs are very widely used in TVSS devices. Like avalanche diodes, MOVs suffer degradation with use, thus limiting the useful life of the entire TVSS unit.

Response time. A measure of the rapidity with which a TVSS device begins to clamp a voltage surge, usually measured in microseconds or nanoseconds. It is not of great significance because both avalanche diodes and MOVs (found in all good-grade TVSS designs) are faster than the voltage buildup time of an incoming surge. Response time is not included in the NEMA standard specification, apparently because it is not considered to be a very important characteristic.

Sinewave tracking. A term of uncertain meaning found frequently in manufacturers' literature.

(b) TVSS Operation

Figure 27.57 is intended to be self-explanatory. Each element acts to reduce the magnitude of the incoming voltage surge by either bypassing (shunting away) current or presenting a high impedance to the voltage surge. Both actions reduce the voltage. A commercial TVSS device may contain any or all of the illustrated components, singly or in multiple, depending upon the current and voltage it is expected to handle.

(c) Standards

Standards applicable to surge-suppression equipment are:

ANSI/IEEE C62.41.1, *Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits*

ANSI/IEEE C62.45, *IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits*

UL 1449, *Standard for Surge Protective Devices*

NEMA LS 1, *Low-Voltage Surge-Protection (LVSP) Devices*

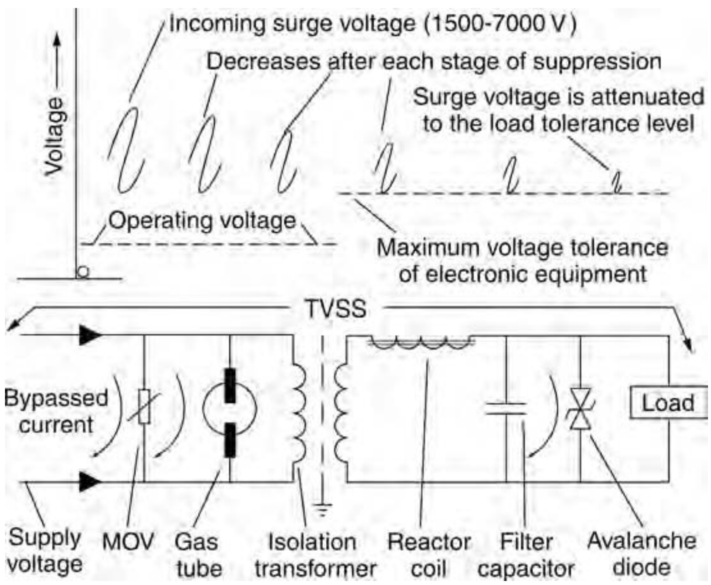


Fig. 27.57 *All of the elements usually found in a surge-suppression device are shown. Each acts to reduce voltage surge—parallel elements by shunting away (bypassing) surge current, and series elements by increasing the electrical impedance to the voltage surge.*

Surge-suppression equipment can be subjected to widely varied voltage stresses, depending upon where in an electrical system a unit is installed. Standard C62.41.1 categorizes installation points according to the severity of service expected, that is, the (electrical) environment in which the surge-suppression equipment operates.

C62.41.1, category C represents the most severe environment, corresponding to locations on the line side of the facility service switches. This environment is subject to the full force of lightning and switching surges and requires robust equipment. As a voltage surge travels through a building's electrical system, it is attenuated by cables, transformers, and other electrical equipment. Therefore, the further along one travels in the building's electrical distribution system, the less severe the voltage surges become. All TVSS devices used in category C environments are hard-wired (Fig. 27.58).

C62.41.1, category B covers environments on the load side of the service equipment, including heavy feeder distribution panels and short branch circuits. Most TVSS devices in category B areas are hard-wired (Fig. 27.59).

C62.41.1, category A, which represents the least-severe service, includes utilization outlets and long branch circuits (because the long cables attenuate a voltage surge). Most category A TVSS devices are arranged for loads to be plugged in directly. Devices used in category A environments include the common cord-connected multioutlet strip and surge-suppression-equipped receptacles (Fig. 27.60).

Each of these three major categories is in turn subdivided into three minor categories: C3, C2, C1; B3, B2, B1; and A3, A2, and A1—where 3 is

Fig. 27.59 *TVSS unit designed to be used at service and branch panelboards in residences and small commercial installations. The illustrated unit is rated single-phase, 120/240 V, 3-wire service, category B3. The unit measures 7 in. W × 7 in. H × 4 in. D (180 × 180 × 100 mm) and is equipped with indicating lights that note power and suppression status. (Photo courtesy of Leviton Manufacturing Co.)*

Fig. 27.58 *Surge suppressor designed for use on the incoming service of a facility. It is rated for category C3 application: shunt type, 120/208 V, 3-phase, unlimited current. It is provided with RFI/EMI filtering and replaceable surge-suppressor modules, and arranged to indicate the power and protection status of each phase. (Photo courtesy of Surge Control Ltd.)*

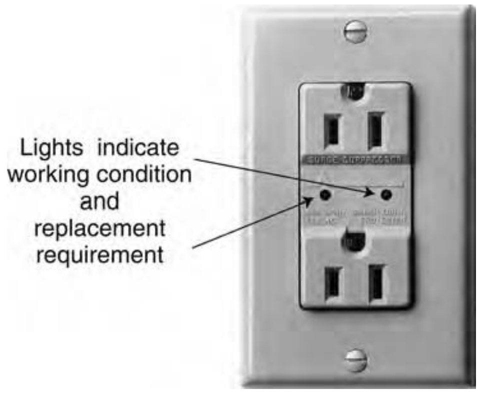


Fig. 27.60 *Typical category A utilization TVSS outlet equipped with indicating lights that show the condition of the surge-suppressor circuitry. (Photo courtesy of Eagle Electric Co.)*

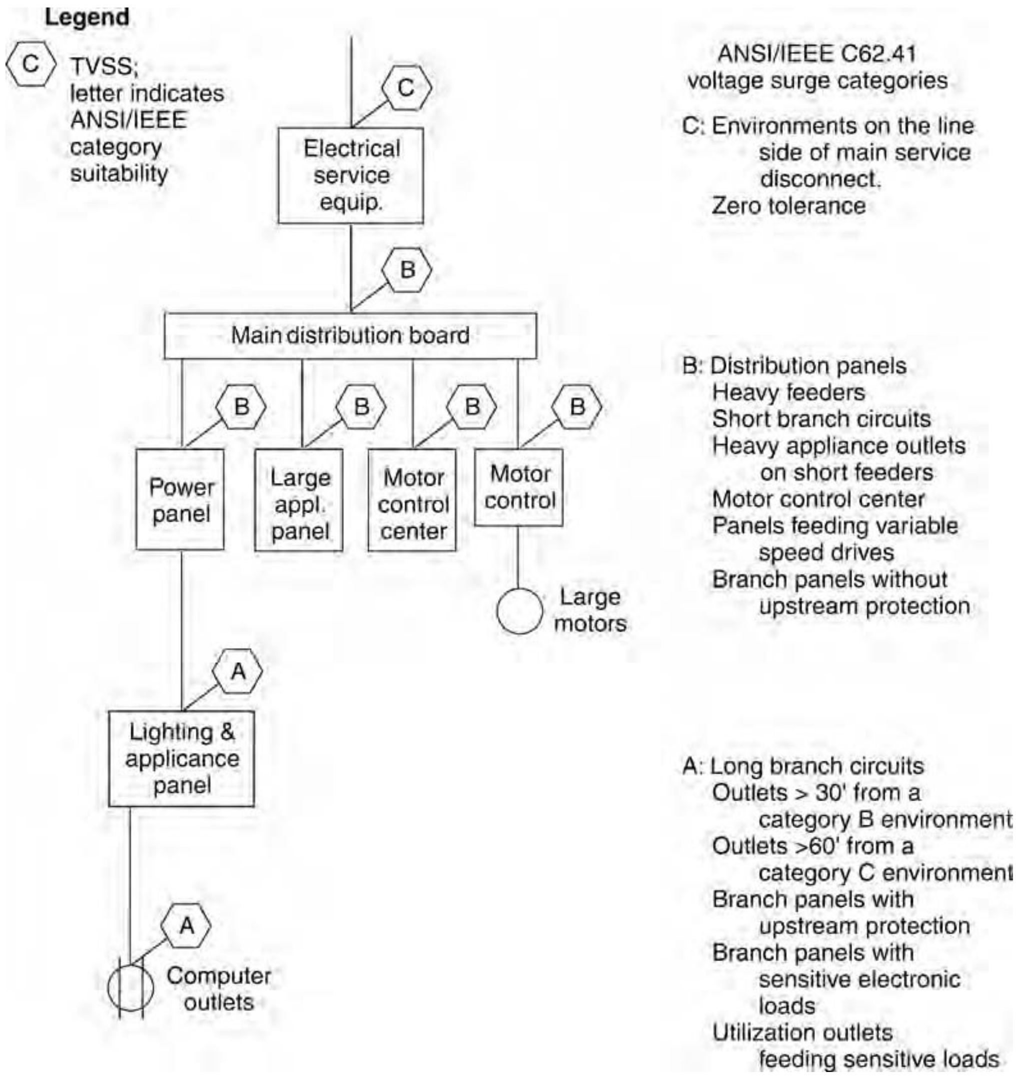


Fig. 27.61 *Illustration based on ANSI/IEEE Standard C62.41.1 showing application of transient voltage-suppression devices in a typical electrical facility, based on the three categories of electrical environments (C, B, A) defined by the standard.*

the most severe and 1 the least. The differentiation depends upon the electrical capacity of the facility's service and distribution system. Large systems have higher surges and less attenuation in the system, thus requiring larger and heavier TVSS equipment than smaller installations. The three major categories are shown graphically with annotations in Fig. 27.61.

Standard C62.45 established the test procedures and test voltage levels to be used by manufacturers in testing and classifying their TVSS products in order to simulate the voltage stresses found in A, B, and C environments.

UL Standard 1449 describes standards for surge-suppressor safety and performance. An important aspect of this standard is that it establishes clamping voltage ratings. The ones of interest to building designers are the lowest four, which are 330, 400, 500, and 600 V. The UL standard requires testing for actual clamping levels, which are then rounded *upward* to one of the standard ratings. Thus, a TVSS that clamps at 240 V and one that clamps at 320 V would both be rated at 330 V, despite the fact that the 240-V unit gives better protection. This distinction is particularly important when protecting computers and other electronic equipment equipped with switching power supplies, and requires a comparison of the *actual* clamping voltage of potential devices rather than simple reliance on the voltage classification.

NEMA LS 1 standardizes the specification format for suppression units, and in so doing establishes a basis for comparison among various manufacturers' products. Important characteristics that must be specified include line voltage, maximum operating current and voltage, maximum surge current, and clamping voltage rating. (Actual clamping voltage is not supplied unless specifically requested, as it involves specific testing.)

All of the aforementioned standards are voluntary industry and technical society publications. In 1997, the U.S. government developed a Performance Verification Test specification that established a quality-grading system for cord-connected surge suppressors. This standard does not correspond readily to the C62.41.1 classifications, except in the B category. It is worth noting that the highest classification in this system is Class 1, Grade A, Mode 1, which corresponds to ANSI category B3, a UL 1449 clamping voltage rating of 330 V, and line-to-neutral protection.

(d) Application of TVSS Devices

Selection and application of surge-suppression devices for even the simplest application require considerable technical background, for which the foregoing material is intended as a primer. Important suggestions to assist in this area are:

- Every power level should have its own TVSS. Small systems can function with C62.41.1 categories B and A only. Large systems may require protection for two or three B levels (B3, B2, B1) and more than one A level.
- In the absence of accurate data on the surge tolerance of electronic equipment, use protection for the most sensitive level. At the utilization level, this is category A3 and U.S. government classification Grade A, Class 1, Mode 1.
- Mode 1 (also called Mode A) indicates protection line-to-line or line-to-neutral. This mode should be specified for stand-alone items. It is preferable to Mode 2 (or B), which is connected line-to-ground, because the latter can introduce random signals (contaminants) into the equipment-grounding system.
- The primary criteria for selection and comparison are the *actual* clamping voltage and maximum surge current capacity. Other important characteristics are those listed in NEMA LS 1.
- TVSS units should be installed as close as possible to the loads being protected.
- Telephone and data lines must also be protected, particularly if the service is overhead. Most telephone companies install an appropriate TVSS at the main distribution frame near the service entrance. This may not be sufficient to protect electronic equipment from a disturbance that can cause distortion of data. A specialist should be consulted to determine the required protection levels and select appropriate equipment (Figs. 27.62 and 27.63).

27.38 UNINTERRUPTIBLE POWER SUPPLY

As explained previously, power-conditioning equipment can supply clean utility power; it cannot, however, supply any power during a utility outage. That eventuality is addressed by providing an alternate supply of power. Facilities with desktop computers, servers, and other data-processing equipment cannot tolerate power outages in excess of about 8 to 50 milliseconds (ms) without serious risk of data loss, and all the negative ramifications of such a loss.

An uninterruptible power supply (UPS) is an arrangement of normal and backup power supplies that transfer a facility's critical load from the normal to the backup supply in so short a time that no computer malfunction results. This transfer time varies somewhat among different schemes and manufacturers but is always less than 8.3 ms, which is the minimum period of power outage that computers must tolerate without disturbance to meet the computer industry's manufacturing guidelines. This time period is double the maximum transfer time required by IEEE Standard 446, *Recommended Practice for Emergency and Standby*

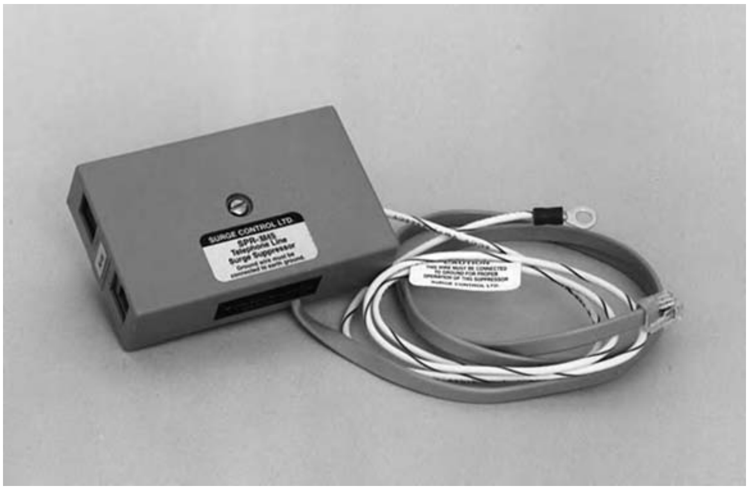


Fig. 27.62 *Surge suppressor designed for use with standard snap-in low-voltage telephone and industry jacks. The illustrated unit is designed to protect telephone/telecommunication lines, both analog and digital. The units are rated 185 V, with a maximum surge current of 5000 A and a test clamping voltage of 240 V. The units can be used with telephones, modems, fax machines, and the like. They measure approximately 4 in. W × 2½ in. H × 1 in. D (100 × 64 × 25 mm). (Photo courtesy of Surge Control Ltd.)*

Power Systems for Industrial and Commercial Applications, of ¼ cycle at 60 Hz, or 4.16 ms. Thus, all computer systems fed from a UPS that meets this standard have a safety factor of at least 2 with respect to transfer time.

Fig. 27.63 *TVSS device designed to protect video lines from voltage transients. The unit plugs into a standard outlet to establish a ground connection for current bypass. This unit is equipped with BNC (Bayonet Neill-Concelman) connections; others have telephone, PL (coaxial), and RS (serial device) connectors for use on telephone, communication, and data lines. The illustrated unit has a clamping voltage of 15 V and a maximum surge current capacity of 5000 A. It measures approximately 2 in. W × 4 in. H × 1 in. D (50 × 100 × 25 mm). (Photo courtesy of Leviton Manufacturing Co.)*

The period of time after transfer that the equipment will run on the standby source depends upon system design. In most cases it is 5 to 10 minutes, which is usually enough time to permit an orderly manual or automatic shutdown. Where shutdown is not a viable alternative, as with computer-controlled manufacturing processes or critical server equipment, the standby power system can readily be designed to supply power indefinitely.

The selection of a UPS system for a facility is a complex process beyond the scope of this book. The material that follows is intended to provide sufficient familiarity with these systems to permit preliminary selection and planning.

(a) Alternate Power Source

For most applications, battery backup is sufficient because only an orderly shutdown is required. Where this is not the case, a two-stage transfer can be used—the first transfer being to a battery backup that can carry the load for up to 1½ hours (or more), depending upon the load magnitude, followed by a second transfer to a long-term standby generator set. Thereafter, the availability of generated standby power is limited only by the fuel supply for the generator. Alternatively, the generator can be maintained online, and the load picked up directly upon the first transfer.

In large industrial installations, the standby source may also be a second utility line. In such cases, only a single transfer is required. Questions of service reliability and equipment redundancy are both technical and economic, and must be studied carefully for each individual installation.

(b) Equipment Arrangement: Classic Standby and Online Topologies

Most UPS systems today are described by their manufacturers as online or simply as UPS rather than standby, primarily because there is no generally accepted industry-wide definition of *online* and also because many systems are hybrid and do not fall easily into either category. Figure 27.64 shows the usual static (nonrotary) UPS equipment arrangement that applies, in principle, to both standby and online modes.

In the standby mode (Path A), utility power is normally passed through some power-conditioning equipment to shield against surges and remove random noise, and then, via position A in the static transfer switch, to the load. The AC line also provides a small current to the small battery charger that keeps the battery fully charged. The DC to AC inverter is open-circuited at the transfer switch and delivers no power. In the event of a utility power failure, the transfer switch moves to position B, and power flows from the battery through the inverter and transfer switch to the load (Path B). With proper equipment design, the transfer is usually accomplished smoothly, although an instantaneous change from no-load to full load on the inverter can sometimes cause a transfer voltage loss. For this reason, online schemes are preferred.

In the straightforward online arrangement shown in Fig. 27.65, power Path A (normal) is through the rectifier and inverter to the load via position B in the transfer switch. The battery floats on the DC line. Failure of utility power causes the power path to change to Path B (i.e., battery to inverter to load). The transfer switch remains in the B position. As a result, voltage to the load is undisturbed. If one of the Path A components fails, the transfer switch moves to position A, and power is supplied directly from the utility lines via Path C, which is referred to as a *utility bypass*. The advantage of the online arrangement is that it eliminates reliance upon the quality of utility power. Power conditioning and surge suppression are provided by the solid-state equipment.

The disadvantages of this classic online topology are high cost due to the full load capacity (size) of the charger/rectifier and an overall efficiency in Path A of about 75% to 80%. The resultant heat production can be problematic and is certainly expensive in terms of power consumption.

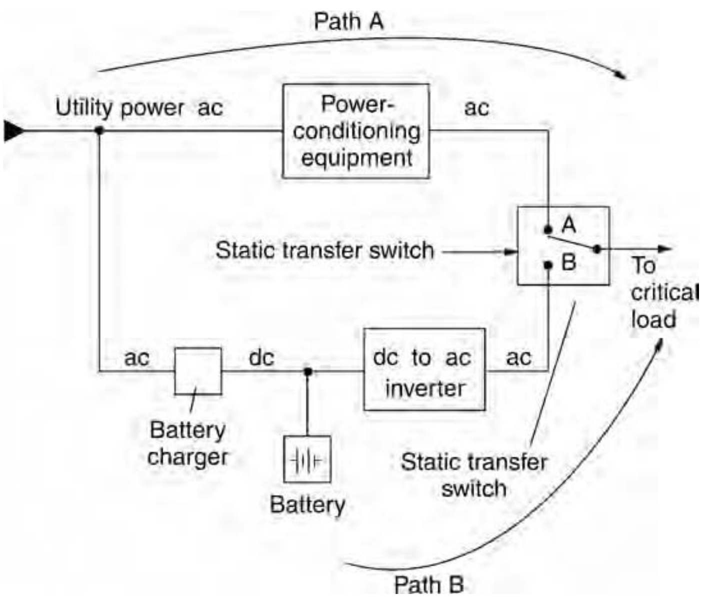


Fig. 27.64 *In this UPS standby arrangement, power normally flows from the utility to the critical (computer) loads through position A of the transfer switch (Path A). The battery floats until a failure of utility power puts it online through the inverter and position B in the solid-state, effectively instantaneous, transfer switch (Path B). The inverter is normally inactive. The battery charger is small because it carries only charging current.*

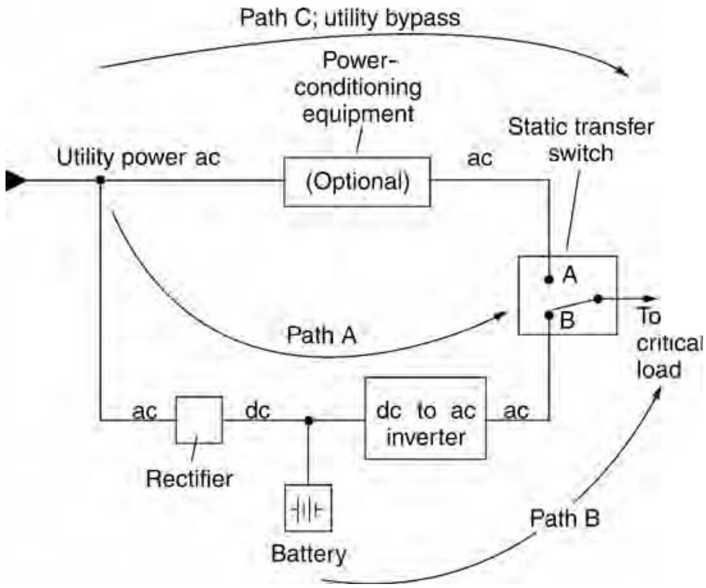


Fig. 27.65 *In this UPS online mode, the normal power Path A is from the utility through a full-size rectifier to the load via an inverter. The battery floats, taking a small charging current from the rectifier. Utility failure brings the battery line through the inverter (Path B). In both instances, the transfer switch remains in position B, and the load senses no change. Only in the event of UPS equipment failure is power taken directly from the utility (Path C).*

(c) Additional UPS Topologies

1. A money-saving arrangement called *online without bypass* is simply the bottom portion of Fig. 27.65. The first cost is reduced by elimination of the transfer switch and considerable cabling. Because failure of any of the components disables the system completely, as there is no backup power path, this system is not recommended for critical loads.

2. A system variously known as *line-interactive*, *standby line-interactive*, and *hybrid interactive* is shown in Fig. 27.66. In its normal mode (Path A), power flows from the utility lines through power-conditioning equipment and position A of the transfer switch to the load. (This is identical to the normal mode of the standby system shown in Fig. 27.64.) In addition, however, utility AC is tapped at the power-conditioning equipment to feed the inverter

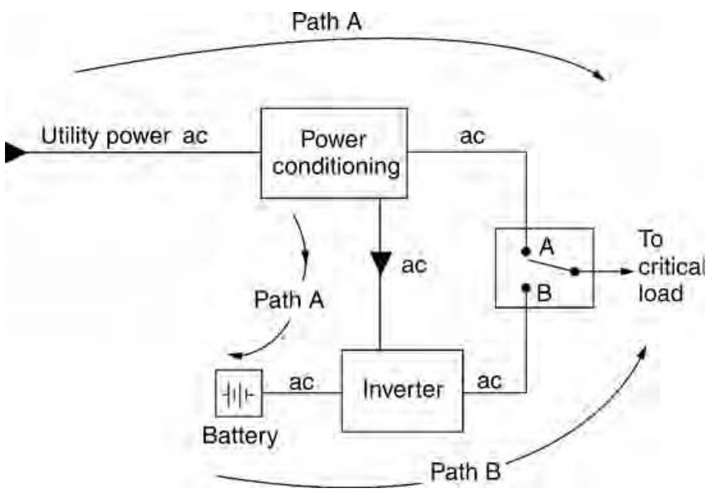


Fig. 27.66 *In this UPS hybrid (line-interactive) mode, the normal power Path A takes power directly from the utility but keeps the inverter online, working in reverse to furnish DC charging current to the battery. Utility failure causes a change to power Path B (i.e., from battery through the inverter now operating normally to invert DC to AC). The static switch changes to position B.*

TABLE 27.8 Typical Dimensional Data for UPS Equipment

Topology	Capacity (kVA)	Dimensions H × W × D in. (mm)	Weight[a] lb (kg)	Full Load Run Time (min.)
Standby	0.3	6 × 6 × 12 (152 × 152 × 305)	15 (6.8)	10
Single phase	0.6	7 × 6 × 14 (178 × 152 × 356)	25 (11.3)	5
Online	3.0	30 × 12 × 24 (762 × 305 × 610)	250 (114)	20
Single phase	7.5	36 × 12 × 36 (914 × 305 × 915)	500 (227)	10
Three-phase	10.0	60 × 24 × 36 (1524 × 610 × 915)	1200 (544)	15
Interactive	0.4	6 × 6 × 12 (152 × 152 × 305)	20 (9.1)	5
Single phase	1.0	8 × 8 × 15 (203 × 203 × 381)	40 (18)	5
	2.0	16 × 8 × 20 (406 × 203 × 508)	105 (48)	20
	3.5	18 × 10 × 24 (457 × 254 × 610)	140 (64)	10

[a]With batteries.

that, operating in reverse as a rectifier (AC to DC), serves as a battery charger.

In the event of a utility power failure, power is drawn from the battery; passing through the inverter, the power is converted to AC. It then connects to the load via the B connection in the transfer switch. The power path is indicated on Fig. 27.66 as Path B. The advantage of this topology is the elimination of a large rectifier by dual use of the inverter and elimination of transients caused by switching on the inverter at full load. The system is efficient, produces little heat, and is highly reliable.

(d) System Selection and Comparison

The preceding system descriptions are intended to provide a topical familiarity with UPS equipment arrangements. Actual selection depends upon the types and magnitudes of the critical loads, detailed outage histories, space considerations, cost factors, equipment and service redundancy, and overall system efficiency. The last characteristic can be a major decision factor where large loads are being supplied, because overall system efficiencies vary from a high of about 95+% for classic standby systems (Fig. 27.64) to as low as 65% for some arrangements. Because all of the power lost to inefficiency turns to heat, a low-efficiency 100-kVA/80-kW system would produce about 27 kW or about 92,000 Btu/h. Unless this heat can be used effectively, power costs and ventilation requirements should be factored into the selection process.

(e) Ancillary Characteristics of UPS Systems

Programmable microprocessors and effective sensors and transducers have been added to basic UPS systems to produce what is known as *intelligent* UPS equipment. These additional devices now make readily available such operating and diagnostic data as battery status, equipment operating temperatures, load data, waveform displays, online power quality analyses, operational and event logs, and the like. These data help an informed operator optimize system functioning, anticipate problems, and keep an accurate printed operational record. Table 27.8 gives some typical dimensional and run-time data for UPS units of different topologies.

27.39 EMERGENCY/STANDBY POWER EQUIPMENT

The *NEC* makes a clear distinction between emergency systems and standby systems, covering the former in Article 700 and the latter in Articles 701 and 702. The equipment, circuitry, and arrangement of both are similar; the purpose is somewhat different. The reader is also referred to NFPA Standard 110: *Standard for Emergency and Standby Power Systems*, which covers equipment requirements for these systems.

Emergency systems are intended to supply electric power to equipment essential for human *safety* upon interruption of the normal power supply. Included in this classification are illumination in areas of assembly (to permit safe exiting and prevent panic) and such other vital functions as fire detection and alarm systems, elevators, fire pumps, public address and communication systems, and orderly shutdown or maintenance of hazardous processes.

Standby systems are divided into two categories: those legally required (Article 701) and optional systems (Article 702). The former are intended to power processes and systems (other than those classified as emergency systems) whose stoppage might create hazards or hamper firefighting operations. This classification goes beyond the emergency systems and could include HVAC systems, water supply equipment, and industrial processes whose interruption could cause a safety or health hazard. It is intended primarily as a safety measure.

Optional standby systems can cover any or all loads in a facility at the discretion of the owner, and are normally intended to protect property and prevent financial loss in the event of a normal service interruption. Examples might include a critical industrial process or equipment for an ongoing research project.

Health-care facilities are covered by a separate set of regulations: *NEC* Article 517 and NFPA Standard 99, both of which are referenced as legally binding in the vast majority of jurisdictional codes. It is important to note that for both emergency and legally required standby systems, the *provision* of the system must be mandated by the authority having jurisdiction over construction, whether it is a local, state, or federal agency or a combination of these. The *NEC* dictates how the system is to be designed and constructed; its existence depends upon another authority.

A case in point is the fundamental issue of exit lighting. This is mandated by the NFPA *Life Safety Code* and Subpart E of OSHA regulations. It is not required by the *NEC*, and reference to *NEC* will not ensure its provision. The code(s) having authority and jurisdiction must specifically require an emergency and/or standby system—by that nomenclature—in order for *NEC* provisions to apply. The precise items of equipment to be powered are selected by the designer, keeping in mind the specific and general requirements of the codes having jurisdiction. The majority of codes make the provisions of the *NEC* and the relevant NFPA standards legally binding. Most codes require emergency systems; far fewer require standby systems, and then only for essential water and water-treatment systems and a few other essential uses. The designer must thoroughly investigate the matter of jurisdictional codes before considering emergency electric power systems and equipment.

System design arrangements are discussed in Sections 29.3 and 29.6. Emergency lighting equipment and system design is covered in Section 17.31. System equipment, which falls into two principal categories—that is, generator and battery installations—is discussed later. Optional standby systems normally use a fueled prime mover rather than batteries.

(a) Engine–Generator Sets

An engine–generator set installation comprises basically three components: a fuel system (including storage, if necessary); the set itself, plus exhaust facilities; and the space housing the equipment (Fig. 27.67). The principal advantages of an engine–generator set are unlimited kVA capacity, duration of power limited only by the size of the fuel tank, use for peak-load shaving, and, if properly maintained, indefinite life. The disadvantages are noise, vibration, the nuisance of exhaust piping and exhaust, the need for constant maintenance and regular testing, and difficulties with fuel storage. Gasoline can be stored for only a year at most, and subsequent disposal is difficult. Diesel fuel keeps somewhat longer, but disposal is also difficult. Use of natural gas for an engine obviates the fuel storage problem but poses the alternate problem of availability of gas service during emergencies. In some large cities, steam is commercially available as an energy source. Here too, service reliability, particularly in the event of a widespread electric service failure, must be carefully investigated.

(b) Battery Equipment

Storage batteries are often used to supply limited amounts of emergency power for lighting (see Section 17.31) and for UPS systems, as detailed previously. Batteries are mounted in individual cabinets or in racks for large installations and are always provided with automatic charging equipment.

Battery types are undergoing intensive development. At this writing, the types principally in use are lead–acid, nickel–cadmium, lead–antimony, lead–calcium cells, and several alkaline types. The choice depends upon the application. Installation requirements such as ventilation, gas detection, isolation, and the like depend entirely upon the type of battery, size of the installation, and battery voltage. Thus, no general guidelines for battery equipment

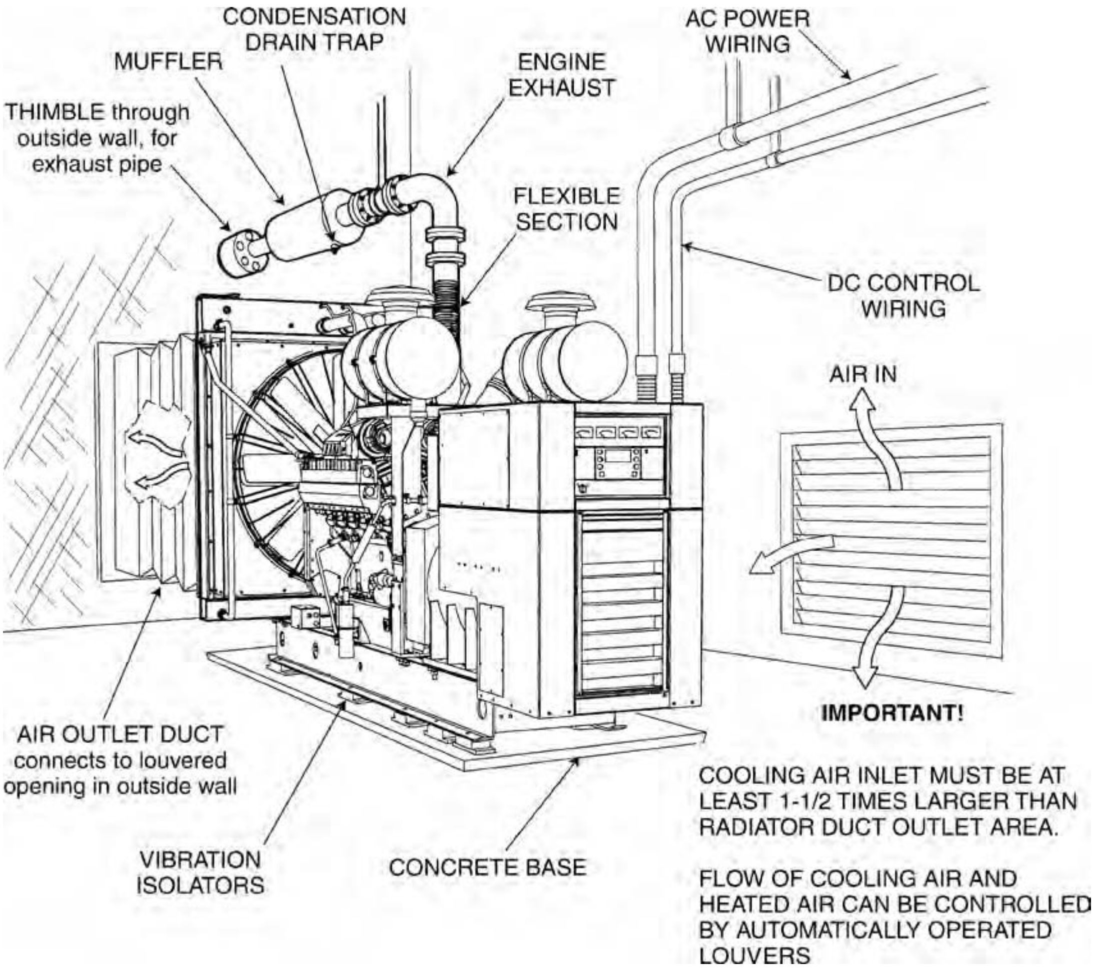


Fig. 27.67 *Typical installation diagram of a radiator-cooled diesel engine–generator set. The set should be oriented so that the hot radiator cooling air vented through an outside wall flows in the same direction as prevailing winds. A solid masonry wind and noise barrier not less than 6 ft (1.8 m) from the radiator air outlet is recommended, as well as an elevated exhaust pipe outlet. (Illustration courtesy of Onan Corp.)*

can be given except to follow *NEC* Article 480 requirements and consult a battery specialist for other data.

Batteries have the distinct advantage that they can be installed either in a central system with distribution of the battery power throughout the facility or in small package units around a building. Central systems are 24 to 125 V, DC or AC, and normally feed emergency lighting only. Individual packs are used often to supply AC power via built-in inverters. The great disadvantage of battery systems is their limited duration of power and their environmental effects upon disposal. The *NEC* requires that batteries maintain loads for a 1½-hour *minimum*, but larger capacity is frequently installed.

27.40 SYSTEM INSPECTION

Each electric wiring system is inspected at least twice by the local inspection authorities: once after raceways (roughing) have been installed and before the wiring and closing-in of walls, and once after the entire job is complete. The purpose of these inspections is to determine whether the design, material, and installation techniques meet the national and local code requirements. Quality of installation is the responsibility of the contractor. The designer, however, must be familiar with installation work and the equipment's physical characteristics in order to properly design an electrical system that will not present the contractor with unwarranted difficulties. The designer must understand and be aware of equipment substitutions by a contractor, who, having submitted a bid on the basis of plans and specifications, should be required to supply the specified equipment. Commissioning of electrical systems to the Owner's Project Requirements is recommended.

C H A P T E R 28

Electrical Systems and Materials: Wiring and Raceways

THE MAJOR COMPONENTS OF A BUILDING ELECTRICAL system can be grouped into three categories: wiring and raceways, power-handling equipment, and utilization equipment. The first category includes conductors and raceways of all types; the second includes transformers, switchboards, panelboards, large switches, and circuit breakers; and the last includes utilization equipment such as lighting, motors, controls, and wiring devices. After an introduction applicable to all electrical materials, this chapter discusses in detail the items in the first of these three categories—that is, the wiring and raceway system. Chapter 27 covers most of the items in the other two categories, with the exception of lighting equipment, which is discussed in Part IV. Signal systems, building control, and automation are discussed in Chapter 31.

28.1 SYSTEM COMPONENTS

Figure 28.1 illustrates how power distribution equipment proceeds from the service point to the utilization points in a progression of decreasing circuit capacity. This is analogous to the arrangement of water supply systems and HVAC systems; the distribution equipment is largest at the supply point, and decreases in size on its way to the farthest utilization points. The reverse is true in collection systems such as those for drainage and venting; in collection systems, piping is smallest at the initial collection points, growing larger (in steps) as the quantities of fluid increase.

A typical single-line diagram does not differentiate by line weight between heavy and light (large and small) conductors (the heavier the conductor, the greater the amount of power being carried), but the single-line diagram of Fig. 28.1 does differentiate in order to show relative power levels throughout the system. This "size" differentiation is more clearly shown in Fig. 28.2, which is a pictorial representation of a system similar to that of Fig. 28.1—but in somewhat greater detail and omitting items beyond the panelboard. Only standard items are shown; special items, however common, such as emergency and uninterruptible power sources, energy controls, service transformers, and the like, are omitted for the sake of clarity.

28.2 NATIONAL ELECTRICAL CODE

The *National Electrical Code* (*NEC*) of the National Fire Protection Association (NFPA) defines the fundamental safety measures that must be followed in the selection, construction, and installation of electrical equipment and systems. This code is used by all

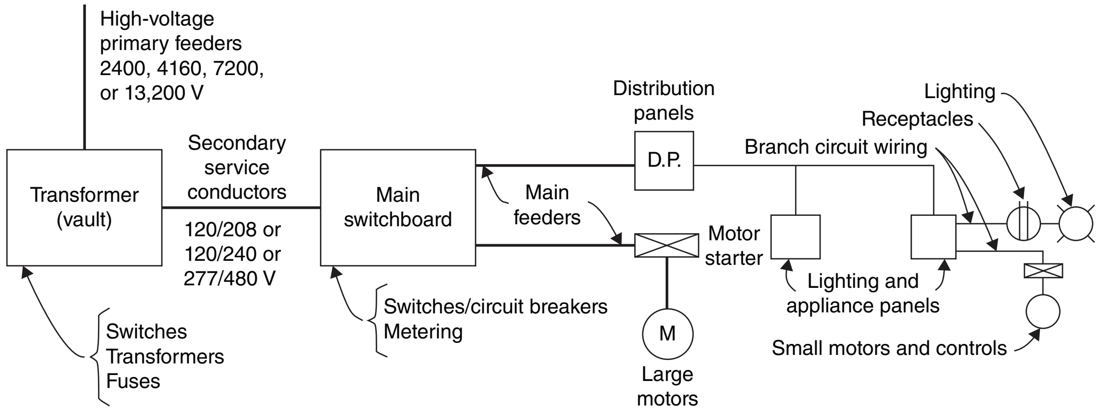


Fig. 28.1 *Single-line diagram of a typical building electrical distribution system, from the incoming service to the utilization items at the end of the system. This is also referred to as a block diagram because the major components are shown as rectangles, or blocks. When this same type of information is presented showing the vertical spatial relationship between components, it is called a riser diagram; when electrical symbols are used in lieu of the blocks, it is called a one-line or single-line diagram. The connecting conductors between the major system components are drawn here with varying thickness to reflect size, and thereby power-handling capacity. In normal practice, all connecting lines are shown the same weight. Also, branch circuits are not usually shown; the typical diagram ends at the lighting and appliance panels.*

inspectors, electrical designers, engineers, contractors, and operating personnel in the United States. Having been incorporated into the Occupational Safety and Health Act of 1970 (OSHA—which is also the acronym for the Occupational Safety and Health Administration, which administers the Act) it has, in effect, the force of law throughout the U.S. Frequent references are made to the *NEC* throughout this chapter. In addition to the *NEC*, many large cities (such as New York, Boston, and Washington, D.C.) have their own electrical codes that, although similar to the *NEC*, contain numerous special requirements.

In order to ensure a minimum standard of intrinsic electrical safety for electrical equipment, a single organization was needed to establish standards and to test and inspect electrical equipment. Underwriters Laboratories (UL) in the U.S. is such an organization, and it publishes extensive lists of inspected and approved electrical equipment. These listings are universally accepted, and many local codes state that only electrical materials bearing the UL label (of approval) are acceptable.

28.3 ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

The selection of electrical materials involves not only choosing a material or assembly that is functionally adequate and, where necessary, visually acceptable, but also the consideration of costs. Usually many types of equipment (from a range of manufacturers) will fulfill the technical requirements of a project. In most cases, final selection of a device or approach hinges upon cost. Ideally, "cost" would be life-cycle cost; more realistically it is often first cost.

The selection decision is relatively simple when various options differ only slightly from each other and a straightforward first-cost comparison is all that is required. Often, however, the choice is not so simple, because materials and equipment may vary considerably in characteristics other than functional suitability, demanding a more detailed cost study. Such economic analyses are frequently performed to make comparisons among competing HVAC systems. This happens less often when dealing with electrical systems because, from an energy point of view, electrical systems are generally less critical (relative to consumption) than HVAC systems, and it is energy costs that are often the decisive factor in economic analyses. Life-cycle system/equipment costs (over the life of the *structure*) are expressed in *present-value* dollars, or annual owning and operating costs, including equipment amortization costs. The type of analysis used will depend upon the situation. Such comparisons are useful, however, only when both the initial cost and the operating costs will be borne by the same individual—that is, an owner-operator. In the case of a

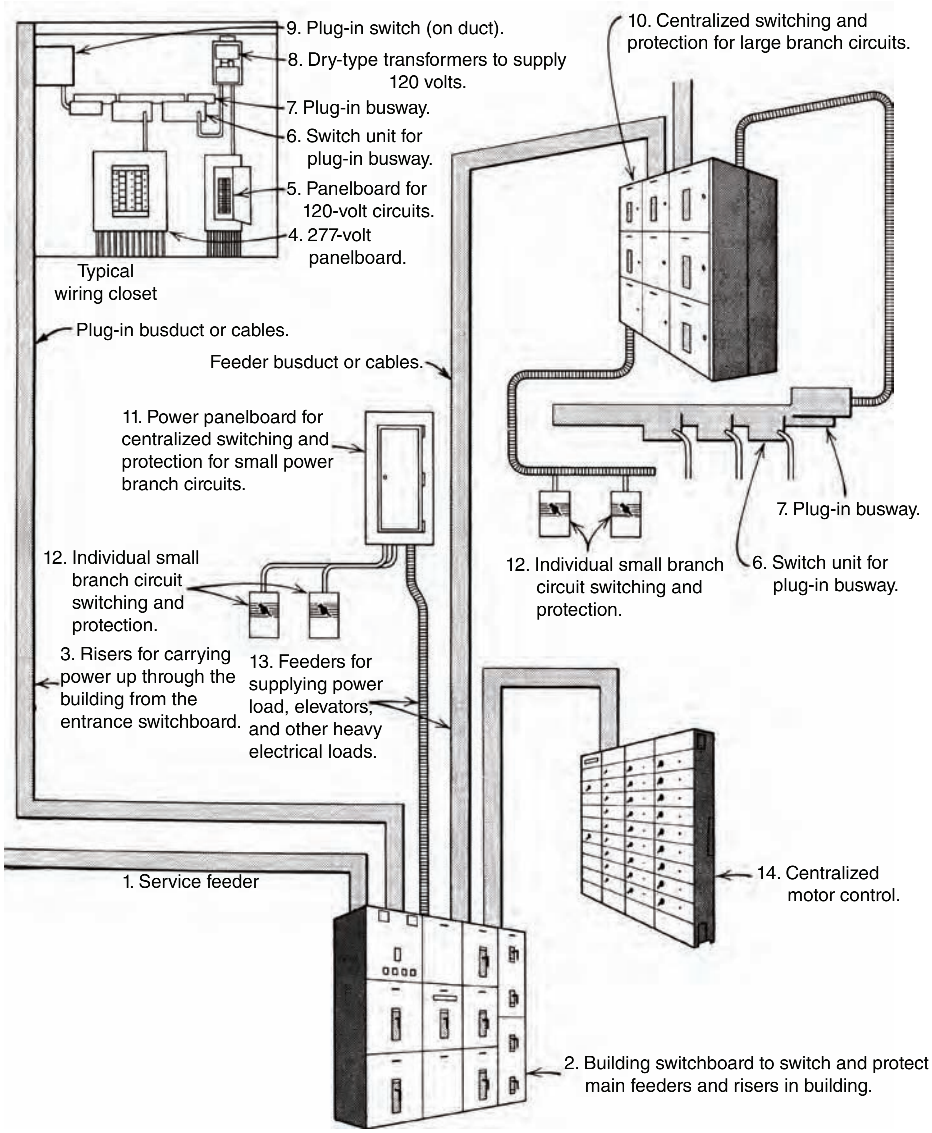


Fig. 28.2 *Diagrammatic (pictorial) representation of a typical building electrical power system with relative power capacity indicated by the size of the conductors. This diagram does not extend beyond the local panelboard and includes only commonly used items. Note also that the entire wiring system is, in effect, jacketed in steel. (Courtesy of General Electric.)*

speculative building venture, first cost is usually the deciding factor for a developer because others will bear the operating costs.

It is often difficult to perform a life-cycle cost analysis because accurate data regarding service life and maintenance costs for electrical equipment may not be readily available. Still, even if a precise analysis cannot be done, the principle involved in life-cycle analysis should be considered in the selection of all electrical materials and equipment, bearing in mind the relative importance to an environmentally responsive building of energy-utilizing and -conveying equipment. See Appendix J for an overview of cost analysis techniques. Economic issues for particular items are found in the following technical discussions.

Energy costs are a major factor in economic analysis. Energy considerations, however, are at least as important in and of themselves because of ever increasing concerns about limited energy and natural resources. This concern is addressed in the context of building energy budgets and their components, including lighting, elevators, and electric motors that are a part of many building systems. Building codes in the U.S. only lightly deal with electrical energy system efficiency—primarily through the requirements presented in ASHRAE Standard 90.1. No explicit recommendation regarding electrical system design is provided in any of the current green building guidelines.

28.4 ELECTRICAL EQUIPMENT RATINGS

All electrical equipment must be rated for the normal service it is intended to perform. These ratings may refer to voltage, current, duty, horsepower, kW, kVA, temperatures, enclosure, and so on. Ratings related to specific equipment are discussed in the sections that follow. The ratings that are specifically and characteristically electrical are those of voltage and current.

(a) Voltage

The voltage rating of an item of electrical equipment is the maximum voltage that can safely be applied to the unit continuously. It frequently, but not always, corresponds to the voltage applied in normal use. An ordinary wall electrical receptacle, for example, is normally rated at 250 V maximum, although in normal use only 120 V are applied to it. The rating is determined by the type and quantity of insulation used and the physical spacing between electrically energized parts.

(b) Current

The current rating of a device is determined by the maximum temperature at which its components can operate at full load. That in turn depends upon the type of insulation used. As a case in point, consider an electric motor. The current flowing in the motor windings causes a power loss (I^2R), which generates heat. If the windings are insulated with varnished cotton braid, with a maximum safe operating temperature of 65°C (150°F), the maximum permissible current (to which the horsepower [kW] rating of the motor is directly related) is the current that produces this operating temperature. If these same windings are insulated with a silicone or glass compound with a maximum operating temperature of 150°C (300°F), more current can be carried safely, and the horsepower (kW) rating is consequently larger. Thus, although a motor is rated in horsepower (or kW), a transformer is rated in kVA, and a cable (discussed later) is rated in amperes, the actual criterion on which all these ratings are based is the maximum permissible operating temperature of the device's insulation (and other components).

28.5 INTERIOR WIRING SYSTEMS

At this point, it is helpful to survey the different types of interior wiring systems before commencing a discussion of components. When the primary purpose of a system is to distribute electrical energy, it is referred to as an *electrical power system*; when the purpose is to transmit information, it is referred to as an *electrical signal* or a *communication system*. This chapter deals with electrical power systems, except that the discussion of raceways covers equipment also used by communication systems.

Due to the nature of electricity, its distribution within a structure for power use poses a single basic problem: how to construct a distribution system that *safely* provides the energy required at the desired locations. The safety consideration is all-important because all parts of an interior distribution system are connected to the utility's powerful network, and the very real potential for physical damage, injury, and fire is always present. The solution to this problem is to isolate all electrically conducting elements from the building structure, except at those specific points, such as wall receptacles, where contact is desired. This isolation is generally accomplished by insulating the conductors and placing them in protective raceways.

The principal types of interior wiring systems in use today are exposed insulated cables, insulated cables in open raceways, and insulated conductors in closed raceways.

(a) Exposed Insulated Cables

This category includes (using the *NEC* nomenclature) cable types NM ("Romex") and AC ("BX"). (See Sections 28.10 and 28.11.) Also included are other types where the cable construction itself provides the necessary electrical insulation and mechanical protection.

(b) Insulated Cables in Open Raceways (Trays)

This system is specifically intended for industrial applications, and it relies on both the cable and the tray for safety.

(c) Insulated Conductors in Closed Raceways

This system is the most general type and is applicable to all types of facilities. In general, the raceway is installed first and the wiring is pulled in or laid in later. The raceways themselves may be:

1. Buried in the structure—for example, conduit in the floor slab or underfloor duct. (See Sections 28.17, 28.18, 28.24, and 28.25.)
2. Attached to the structure—for example, all types of surface raceways, including conduit and wireways suspended above hung ceilings. (See Sections 28.22 and 28.29.)
3. Part of the structure—for example, cellular concrete and cellular metal floors. (See Sections 28.26 and 28.27.)

(d) Combined Conductor and Enclosure

This category is intended to cover all types of factory-prepared and factory-constructed integral assemblies of conductor and enclosure. Included here are all types of busway, busduct, and cablebus (Section 28.14); flat-cable assemblies and lighting track (Section 28.15); flat cable intended for undercarpet installation (Section 28.29); and manufactured wiring systems (Section 28.30).

28.6 CONDUCTORS

Electrical conductors ("wires") are the means by which current is conducted through the electrical system, corresponding to the piping of a hydraulic system. The standard of the U.S. wire and cable industry for round cross-section conductors is the American Wire Gauge (AWG). By convention, a single insulated conductor No. 6 AWG or larger, or several conductors of any size assembled into a single unit, are referred to as *cable*. Single conductors No. 8 AWG and smaller are called *wire*.

All wire sizes up to No. 0000 (also written as No. 4/0) are expressed in AWG. The AWG numbers run in *reverse* order to the size of the wire—that is, the smaller the AWG number, the larger the size. Thus, No. 10 is a heavier wire than No. 12 wire and is lighter (thinner) than No. 8 wire. The No. 4/0 size is the largest AWG designation, beyond which a different designation called *kcmil* (thousand circular mil) is used. In this designation, wire diameter *increases* with number; thus, 500 kcmil is a heavier wire (double the area) than 250 kcmil. The former designation for this unit was *MCM*, a term that is still used in many sources.

Outside of the United States, where SI units are in general use, conductor sizes are given simply by their diameter in millimeters. Table 28.1 gives dimensional and stranding data for common wire sizes and includes the millimeter equivalent of each size. This will prove useful in relating American gauges to SI sizes.

28.7 CONDUCTOR AMPACITY

As noted, conductor current-carrying capacity, or *ampacity*, is determined by the maximum safe operating temperature of the insulation used on the conductor. Heat generated as a result of current flow is dissipated into the environment. Thus, for a given installation context (open-air, buried in earth, or enclosed), ampacity increases with increasing conductor size *and* with maximum permissible insulation temperature. This is shown in Table 28.2. If more than three conductors are placed in a conduit, the resultant increase in temperature requires that the conductors be derated by the amount shown in Table 28.3 to maintain safe operating conditions.

Because heat dissipation from a conductor in free air is much greater than that from the same conductor enclosed in conduit or directly buried, its corresponding allowable ampacity is also greater. Conversely, if the ambient temperature around a conductor is higher than 30°C (86°F), the temperature upon which all standard ampacity tables are based, the permissible ampacity must be reduced.

TABLE 28.1 Physical Properties of Bare Copper Conductors

Size AWG kcmil (MCM)	Area Circular Mils	Diameter (in.)		Diameter (mm)		DC Resistance at 25°C (77°F) (Uncoated) ohms/1000 ft (305 m)
		Solid	Stranded	Solid	Stranded	
18 AWG	1620	0.040	—	1.02	—	7.77
16	2580	0.051	—	1.29	—	4.89
14	4110	0.064	—	1.63	—	3.07
12	6530	0.081	0.092	2.05	2.34	1.93
10	10,380	0.102	0.116	2.59	4.06	1.21
8	16,510	0.128	0.146	3.26	3.71	0.764
6	26,240	—	0.184	—	4.11	0.491
4	41,740	—	0.232	—	5.18	0.308
2	66,360	—	0.292	—	6.55	0.194
1	83,690	—	0.332	—	7.34	0.154
0 (1/0)	105,600	—	0.373	—	8.26	0.122
00 (2/0)	133,100	—	0.418	—	9.27	0.097
000 (3/0)	167,800	—	0.470	—	10.41	0.077
0000 (4/0)	211,600	—	0.528	—	11.68	0.061
250 kcmil	250,000	—	0.575	—	12.70	0.052
300 kcmil	300,000	—	0.630	—	13.92	0.043
400 kcmil	400,000	—	0.728	—	16.05	0.032
500 kcmil	500,000	—	0.813	—	19.56	0.026

Source: Reprinted with permission from NFPA 70® – 2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02169. All rights reserved. The dimensions in mm were added by the authors.

Ampacity tables for conductors in free air, for cable types not shown in Table 28.2, and derating factors for high ambient temperatures are all found in the *NEC*. Typical ambient temperatures are given in Table 28.4.

28.8 CONDUCTOR INSULATION AND JACKETS

Most conductors are covered with some type of insulation that provides both electrical isolation and a degree of physical protection. Additional physical shielding, where necessary, is provided by a jacket placed over the insulation. Insulation is rated by voltage. Ordinary building wiring is rated for either 300 or 600 V. Common types of building wire insulation are listed in Table 28.5 with their associated trade names, code letters, maximum permitted operating temperatures, and special provisions.

28.9 COPPER AND ALUMINUM CONDUCTORS

Aluminum has an inherent weight advantage over copper, which brings with it lower installation costs. Economy usually lies with copper in small- and medium-sized cable, because weight is not a problem, and the smaller conduit required for the smaller copper conductors generally makes the combined installation cheaper. In larger cable sizes, the aluminum weight advantage offsets the economy of smaller copper size and conduit, and aluminum generally proves less expensive, particularly in urban areas with high labor costs.

Aluminum and copper both exhibit the low electrical resistivity necessary for a good electrical conductor. There are, however, difficulties inherent in splicing and terminating aluminum. These difficulties—which can be overcome with the use of proper equipment, techniques, and workmanship—stem from aluminum's cold-flow characteristic when under pressure (causing joints to loosen) and aluminum's oxide. This oxide, which forms within minutes on any exposed aluminum surface, is an adhesive, poorly conductive film that must be removed and prevented from reforming if a successful, long-life joint or termination is to be made. If this is not done, the oxide causes a high-resistance joint with excessive heat generation and possible incendiary effects. The oxide problem can be largely overcome by the use

TABLE 28.2 Allowable Ampacities of Insulated Conductors Rated 0 through 2000 V, 60° to 90°C (140° to 194°F), Not More Than Three Current-Carrying Conductors in Raceway or Cable or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)

PART A			
	Temperature Rating of Conductor[a]		
	60°C (140°F)	**75°C (167°F)**	**90°C (194°F)**
Size AWG, kcmil	**Type UF**	**Types RHW, THW, THWN, XHHW**[b]	**Types THHN, XHHW**[b]
14 AWG[c]	20	20	25
12[c]	25	25	30
10[c]	30	35	40
8	40	50	55
6	55	65	75
4	70	85	95
2	95	115	130
1	110	130	150
0	125	150	170
00	145	175	195
000	165	200	225
0000	195	230	260
250 kcmil	215	255	290
300	240	285	320
350	260	310	350
400	280	335	380
500	320	380	430

PART B				
Ambient Temperature		*Correction Factors for Ambient Temperatures Other Than 30°C (86°F), Multiply the Allowable Ampacities Shown Above by the Appropriate Factor Shown Below.*		
°C	**°F**			
21–25	70–77	1.08	1.05	1.04
26–30	78–86	1.00	1.00	1.00
31–35	87–95	.91	.94	.96
36–40	96–104	.82	.88	.91
41–45	105–113	.71	.82	.87

Source: Reprinted with permission from NFPA 70® – 2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02169. All rights reserved.

[a]See Table 28.5.

[b]For dry and damp locations use the 90°C (194°F) rating; for wet locations use the 75°C (167°F) rating.

[c]Unless otherwise permitted by the *NEC*, the overcurrent protection for these conductors shall not exceed 15 A for 14 AWG, 20 A for 12 AWG, and 30 A for 10 AWG, after application of correction factors for ambient temperature and number of conductors in raceway.

of copper-clad aluminum wire, but the cold-flow problem remains. Furthermore, when used in residential branch circuits, aluminum can create problems (even if properly installed initially) when wiring devices are replaced by unskilled homeowners.

As a result of a number of unfortunate incidents, some jurisdictions in the United States have banned the use of aluminum wire in branch circuitry. Heavy feeders are normally installed by experienced and skilled contractors, and the risk of a poor joint is minimized. We recommend that the use of aluminum conductors be restricted to sizes no smaller than No. 4 AWG, and that installation be permitted *only* by contractors who certify expertise in the specialized techniques involved. Also, local codes and electrical inspectors should be consulted. All references in this text, including all tables and illustrations, are to copper conductors. The following sections provide a brief description of the principal building wire types.

TABLE 28.3 Current-Carrying Capacity Derating Factors[a]

Number of Current-Carrying Conductors in Raceway[b]	Derating Factor[c]
4–6	0.80
7–9	0.70
10–20	0.50
21–30	0.45
31–40	0.40
41 and above	0.35

Source: Reprinted with permission from NFPA 70® – 2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02169. All rights reserved.

[a]These factors are to be applied after application of derating factors for ambient temperatures other than 30°C (86°F). See Table 28.2.

[b]Grounding and bonding conductors are not counted. Neutral conductors are counted in special cases. See 2011 *NEC*, Article 310–15(B)(5).

[c]When a load diversity factor is applicable, derating factors as given in 2011 *NEC* Annex B Table B.310.15(B)(2)(11) shall be used.

TABLE 28.4 Typical Ambient Temperatures

Location		Temperature
Well-ventilated, normally heated buildings		30°C (86°F)
Buildings with major heat sources such as power stations or industrial processes		40°C (104°F)
Poorly ventilated spaces such as attics		45°C (113°F)
Furnaces and boiler rooms	(min.)	40°C (104°F)
	(max.)	60°C (140°F)
Outdoors in shade in air		40°C (104°F)
In thermal insulation		45°C (113°F)
Direct solar exposure		55°C (131°F)

28.10 FLEXIBLE ARMORED CABLE

Among the most common types of exposed wiring is *NEC* type AC armored cable, commonly known in the smaller sizes by the trade name *BX*. It is an assembly of insulated wires, bound together and enclosed in a protective armor made of a spiral-wound interlocking strip of steel tape (Fig. 28.3). The cable is installed with simple U-clamps or staples holding it against beams, walls, and so on. This type of installation is frequently used in residences and in the rewiring of existing buildings. Use of type AC cable is generally restricted to dry locations. For application and installation details and restrictions, see *NEC* (2014) Article 320, "Armored Cable."

A similar construction with much broader application (covered in *NEC* Article 330) is metal-clad (MC) cable. This cable (Fig. 28.4) may be used exposed or concealed and in cable trays, and, when covered with a moisture-impervious jacket, in wet and outdoor locations as well.

28.11 NONMETALLIC SHEATHED CABLE (ROMEX)

NEC types NM and NMC (Fig. 28.5), also known by the trade name *Romex*, are restricted to small building applications—that is, residential and other structures not exceeding three floors above grade. The plastic outer jacket, unlike the armor on type AC, makes type NM easier to handle but more vulnerable to physical damage. For application details and restrictions, see *NEC* Article 334, "Non-metallic Sheathed Cable." The typical installation technique is shown in Fig. 28.6.

TABLE 28.5 Conductor Insulation and Application

Trade Name	Type/Letter	Temperature	Application Provisions
Moisture and heat-resistant rubber	RHW	75°C (167°F)	Dry and wet locations
Single conductor, underground feeder and branch-circuit	UF	60°C (140°F) 75°C (167°F)[a]	Refer to *NEC* Article 339
Moisture-resistant thermoplastic	TW	60°C (140°F)	Dry and wet locations
Heat-resistant thermoplastic	THHN	90°C (194°F)	Dry and damp locations
Moisture and heat-resistant thermoplastic	THW	75°C (167°F) 90°C (194°F)	Dry and wet locations Special applications
Moisture and heat-resistant thermoplastic	THWN	75°C (167°F)	Dry and wet locations
Moisture and heat-resistant cross-linked synthetic polyethylene	XHHW	90°C (194°F) 75°C (167°F)	Dry and damp locations Wet locations

Source: Reprinted with permission from NFPA 70® – 2011, *National Electrical Code*®, Copyright © 2010, National Fire Protection Association, Quincy, MA 02169. All rights reserved.

[a]For ampacity limitation, see 2011 *NEC* Article 340–80.

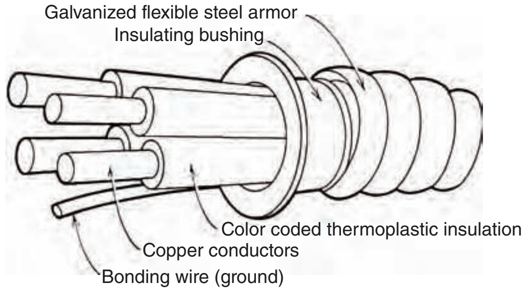
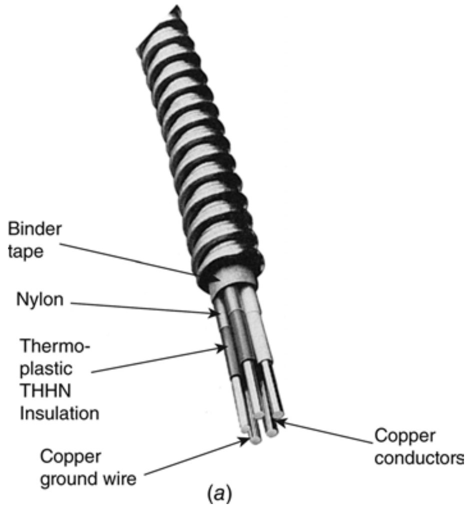
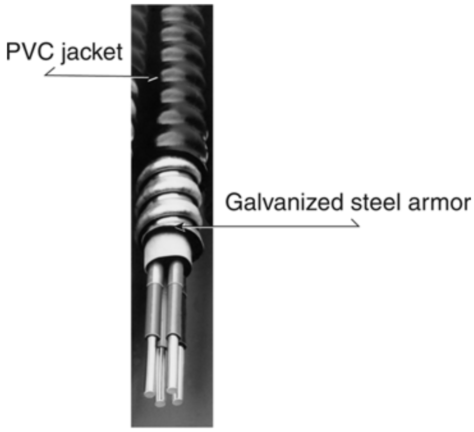


Fig. 28.3 *Flexible armored cable (*NEC *type AC, trade name BX). Note the insulating bushing that is always installed on the end of the armor to protect the wires from damage from the sharp edges of the cut steel armor. (Courtesy of AFC Cable Systems.)*



(*a*)



(*b*)

Fig. 28.4 *(a) Metal-clad cable (*NEC *type MC, Article 330) with aluminum armor in lieu of the more common galvanized steel armor. Use is similar to that of the steel-armored cable, with the weight advantage of aluminum. Conductors are factory-installed, color-coded, and covered with type THHN insulation and nylon jacket. Cables of similar construction, using steel armor, are available for almost all power and control applications. (Courtesy of AFC Cable Systems.) (b) Jacketed-type MC cable has a wide variety of applications, including in wet locations, because of its water-impervious outer PVC jacket. Where specifically indicated by the manufacturer, this cable may be used for direct burial in earth or installed in concrete. (Courtesy of AFC Cable Systems.)*

28.12 CONDUCTORS FOR GENERAL WIRING

Under this heading (Article 310), the *NEC* lists the wire types that are generally installed in raceways and are referred to by the term *building wire*. The most common types are listed in Table 28.5. These wires consist of a copper conductor covered with insulation and, in some instances, with a jacket (Fig. 28.7).

28.13 SPECIAL CABLE TYPES

Although most building wiring is accomplished with plastic-insulated 300- and 600-V conductors of the types described in the preceding sections, some applications require the use of special cables. These include high-voltage cables, armored cables, corrosion-resistant jacketed cables, underground cables, and so on. The reader is referred to manufacturers' catalogs and the *NEC* for construction and application details. Service-entrance cables and their installation are discussed in Sections 27.1 through 27.4.

28.14 BUSWAY/BUSDUCT/CABLEBUS

A busway (busduct) is an assembly of copper or aluminum bars in a rigid metallic housing (Fig. 28.8). Its use is almost always preferable, from an economic viewpoint, in two instances: when it is necessary to carry large amounts of current (power) and when it is necessary to tap onto an electrical power conductor at frequent intervals along its length.

In the case of a heavy current requirement, the alternatives to using busways are to use paralleled sets of round conductors or a single large conductor. Paralleled sets of conductors are almost always more expensive than a busway of similar current capacity because of the high installation cost of multiple conduits. Alternatively, using a single, large-diameter

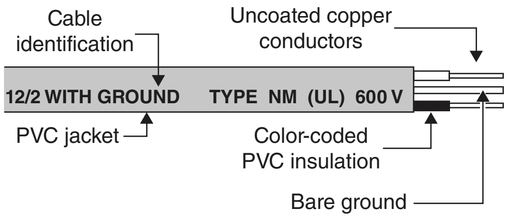


Fig. 28.5 *Construction of typical* NEC *type NM cable. The illustrated cable is a two-conductor, No. 12 AWG with ground, insulated for 600 V. Normally shown are the manufacturer, cable trade name, and the letters (UL), which indicate listing of this product by Underwriters Laboratories, Inc. The ground wire is bare or covered, and the entire cable may be obtained flat (illustrated), oval, or round.*

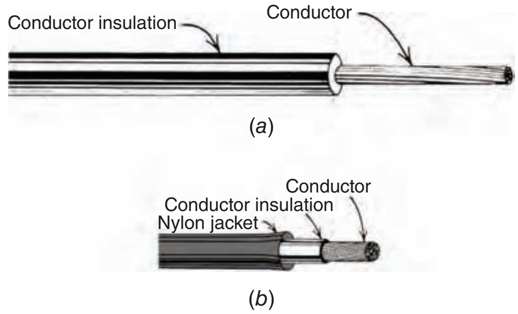


Fig. 28.7 *(a) Typical construction of unjacketed building wire such as type THW (see Table 28.5). (b) The illustrated construction is typical for any nylon-jacketed cable such as THWN or THHN. (The first three letters indicate the type of insulation, and the final N indicates the nylon jacket.)*

conductor becomes increasingly inefficient as cable size increases because large round conductors require more cross section per ampere of current-carrying capacity than do the flat conductors (busbars) used in busduct (Fig. 28.9).

Where many power taps are required along an electric feeder run consisting of cable in conduit, costs become very high because of the large amount of expensive hand labor involved, since a connection must be made to each conductor in the run. The preferable alternative is to use a "plug-in" busway to which connections can be made easily and rapidly with a plug-in device, similar to the insertion of a common plug into a wall receptacle. This has the additional advantage of convenience; connection/disconnection is simply a matter of inserting or withdrawing the plug-in device, whereas cable taps are permanent connections (Fig. 28.10).

A typical application of heavy-duty busduct might be a vertical feeder in a high-rise building connecting the basement switchboard to the penthouse machine room. The same building might also

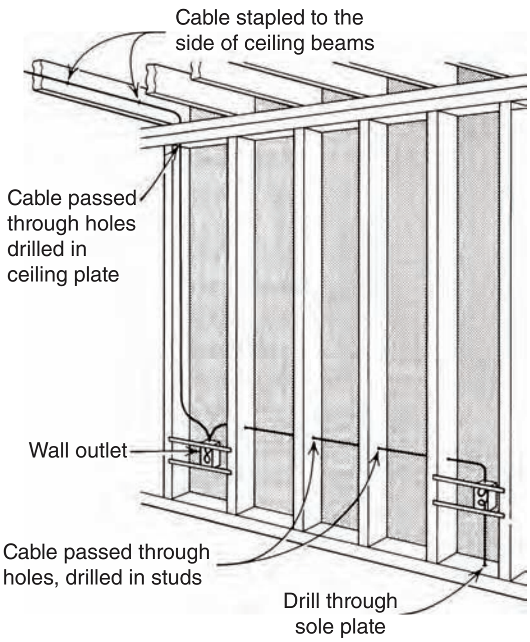


Fig. 28.6 *Typical wiring technique using types NM (Romex) or AC (BX) in wood stud construction. With metal stud construction, BX cables are passed through precut openings in lieu of field-drilled holes. Where cables are exposed to damage from nails, screws, and other hazards, protective metal cover plates are required. For details, see the installation limitations in the* NEC.

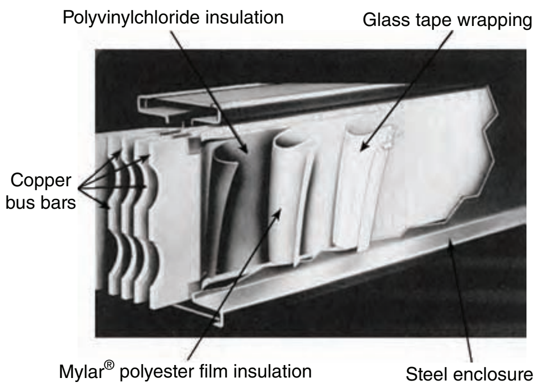


Fig. 28.8 *Cutaway view showing construction of a typical feeder busduct. This design is highly compact and rigid, which gives desirable electrical characteristics as well as the advantage of small size. (Photo courtesy of Siemens Energy and Automation, Inc.)*

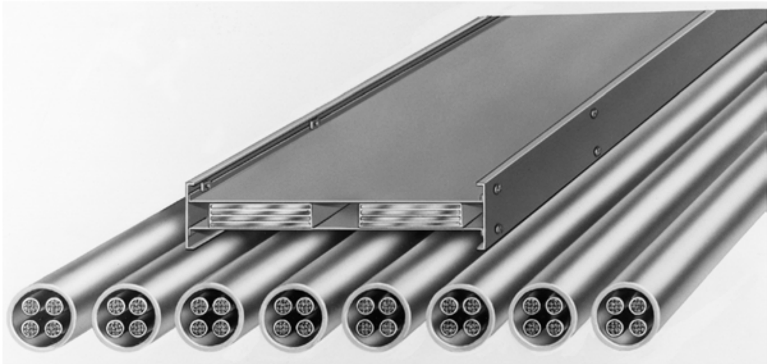


Fig. 28.9 Sectional view of a busduct (on top) shows the tight assembly of insulated conductors within a metal housing. This design, unlike the ventilated type, can be mounted in any position because heat dissipation is by conduction from the busbars to the housing. The eight sets of cable (shown on the bottom) have the same current-carrying capacity as the busduct. (Reproduced by permission of Square D Company.)

use heavy-duty plug-in busduct as vertical riser(s) with taps feeding individual floors (Fig. 28.2). Typical applications for light-duty plug-in busduct (70 to 100 A) could be any machine shop or workshop. The electrical supply to individual machine tools is made very simply and flexibly with a tap-on device (see Fig. 28.10).

Busduct is specified by type, material, number of buses, current capacity, and voltage (e.g., aluminum feeder busduct, 4-wire, 1000 A, 600 V, or copper plug-in busway, 100 A, 3-wire, 600 V). Feeder busduct (no plug-in capability) is available in ratings from 400 to 4000 A. Plug-in busway is available from 30 A for lighting or light-machinery circuits (see Section 28.15) to 3000 A. A wide variety of fittings and joints are available for all busways to permit easy installation (Fig. 28.11). Devices are available for indoor and outdoor application.

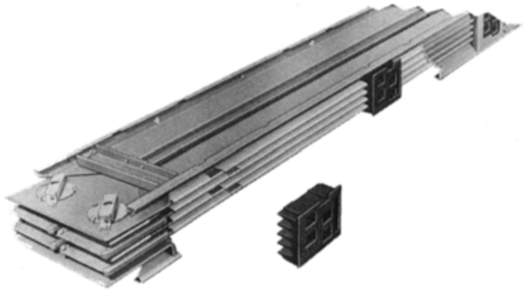


Fig. 28.10 Construction of one type of plug-in busduct. Plug-ins are evenly spaced on alternate sides to facilitate connection of plug-in breakers, switches, transformers, or cable taps. Housing is of sheet steel with openings for ventilation. The cover plate is not shown. (Courtesy of Square D Company.)

Cablebus is similar to ventilated busduct, except that it uses insulated cables instead of busbars. The cables are rigidly mounted in an open space-frame. The advantage of this construction is that it carries the ampacity rating of its cables *in free air*, which is much higher than for the same cables in conduit, thus giving a high amperes-per-dollar first-cost figure. Its principal disadvantages are bulkiness and difficulty in making taps.

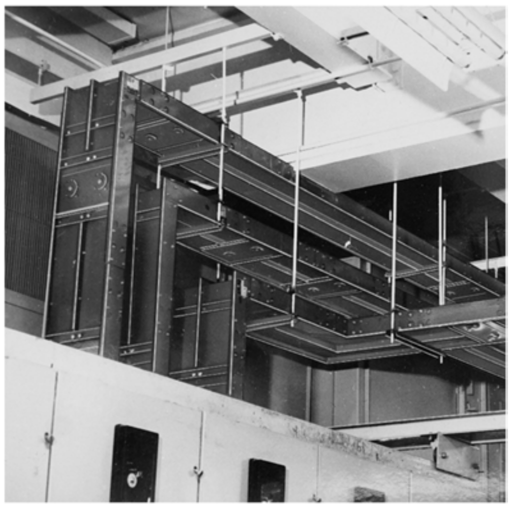


Fig. 28.11 Typical installation of compact-design busduct. Note that the individual busducts are supported by channels hung from the ceiling and that the same hangers support more than one level of bus. Right-angle turns are easily made in the same plane (horizontal or vertical) and between vertical and horizontal planes. (Reproduced by permission of Square D Company.)

TABLE 28.6 Life-Cycle Relative Cost Comparison of 2000-A, 208-V Feeder Installation

Feeder System Description[a]	Material Cost	Labor Cost[b]	Total First Cost	Power Loss per 100 ft[c] (kW)	Annual Energy Loss[d] (kWh)	Annual Energy Cost[e]	Life-Cycle Energy Cost[f]	Total Life-Cycle Cost[g]
Cable tray	0.63	0.37	1.00	2.90	12,536	0.086	1.081	2.08 100%
Wire and conduit	0.68	0.61	1.29	2.90	12,536	0.086	1.081	2.37 114%
Busduct	1.14	0.24	1.38	5.60	24,207	0.166	2.087	3.47 167%
Cablebus	0.69	0.45	1.14	5.91	25,547	0.174	2.203	3.34 161%

[a]Equipment rating is 600 V, cable is copper, conduit is rigid steel, cable tray is aluminum.

[b]Labor cost includes overhead.

[c]Based on published resistivity data for cable and bus—assuming 80% demand (1600 A) and all conductors in the system equally loaded. (Loss is equivalent to kW per 30.5 m.)

[d]Based on 80% demand, 12 hours per day, 360 days per year.

[e]Using $0.10 per kWh as the combined net rate, including demand charges.

[f]Using a 20-year life cycle, 8% fixed capital cost, and 3% annual escalation in energy cost.

[g]Sum of the fourth and eighth columns.

An example of the type of economic analysis that should be made when considering an item as fundamental as a heavy-current electrical feeder, is summarized in Table 28.6, which shows the results of such a study in terms of relative costs. Note that when considering first cost alone, the advantage lies with cable tray (with interlocked armor cables) and cablebus. Adding energy-loss considerations shifts the advantage to cable tray and wire in conduit. No general conclusion should be drawn from Table 28.6 regarding costs. A change in feeder length, number of taps, hours of operation, energy costs, or any of the other factors can shift the advantage to a different system. The point of the study is to demonstrate that life-cycle costs and first costs often lead to entirely different conclusions and that this type of study is truly required before a rational engineering decision can be made. (Life-cycle cost in this example was taken as the present value of all costs over the installation's life cycle—in this case, 20 years.)

Two additional items are worthy of note:

1. The very factors that yield a lower first cost operate to yield a higher operating cost. The smaller copper sizes in busduct and cablebus, permitted by high-temperature insulation and good ventilation, cause increased power loss because of their higher resistivity.
2. If the heat loss from the busduct or cablebus can be used to advantage, the related energy cost can be credited instead of being considered a total loss, and life-cycle costs can be changed considerably. Conversely, the heat generated can negatively affect the building cooling load.

28.15 LIGHT-DUTY BUSWAY, FLAT-CABLE ASSEMBLIES, AND LIGHTING TRACK

Special prefabricated assemblies that act as light-duty (branch circuit) plug-in electrical feeders are widely used because of their simplicity of installation and, more importantly, because of their plug-in mode of connection.

(a) Light-Duty Plug-In Busway

This construction, which may be used either for feeder or branch circuit applications, is covered by the *NEC* general article on busways, with restrictions when applied as branch circuit wiring. Light-duty busways are rated from 20 to 60 A at 300 V, in 2- and 3-wire construction. A somewhat heavier design rated 60 A to 100 A at 600 V is available in 3- and 4-wire construction. Their application is principally for direct connection (with overcurrent protection) of light machinery and industrial lighting (Figs. 28.12 and 28.13).

Fig. 28.12 *Light-duty busway is rated 20—60 A, 300 V, and either 2- or 3-wire. Power takeoff devices twist into the bus to make contact with the circuit conductors. Within* NEC *restrictions of overcurrent protection, this busway may be used for standard and heavy-duty lighting fixtures and for other electrical devices such as electrically powered tools. (Courtesy of Siemens Energy and Automation, Inc.)*

(b) Flat-Cable Assemblies

A specially designed cable (*NEC* Article 322; Type FC) consisting of two, three, or four No. 10 AWG conductors is field-installed in a rigidly mounted standard 1⅝-in. (41-mm) square structural channel. Power-tap devices, installed where required, puncture the insulation of one of the phase conductors and the neutral. Electrical connection is then made to the pigtail wires that extend from the tap devices. This connection can extend directly to the device or to an outlet box with a receptacle, which then acts as a disconnecting means for the electric

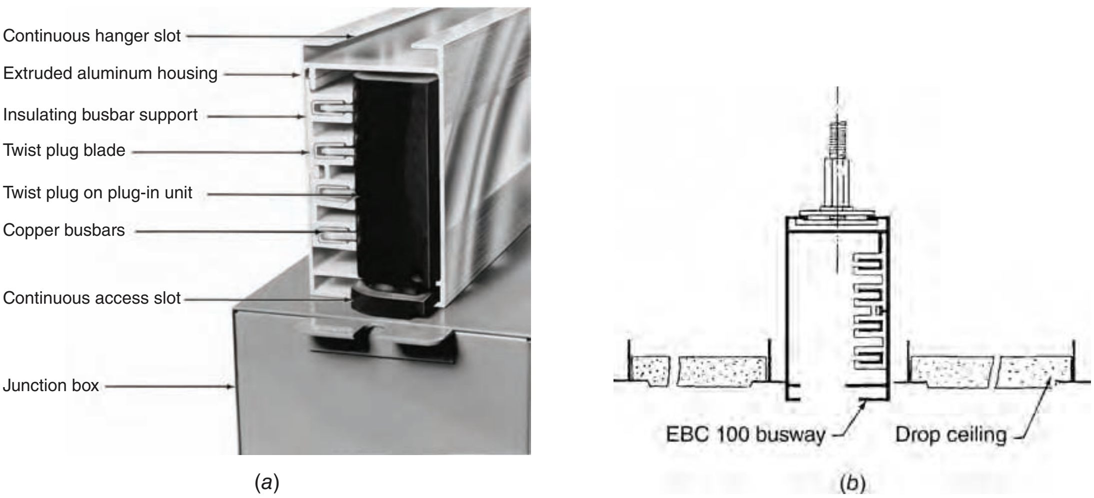


Fig. 28.13 *(a) Plug-in busway rated 100 A, 3-phase, 4-wire, 600 V measures approximately 2½ in. W × 4½ in. H (64 × 115 mm). The twist-in plug, which is integrally attached to a connection means (junction box in the illustration), is rated 30 to 100 A, single- or 3-phase, as required. The attached junction box (or receptacle, circuit breaker, or fuse box) then feeds the utilization device (e.g., heavy-duty lighting or machinery). (b) This bus can also be installed in a hung ceiling. (Courtesy of Universal Trolley.)*

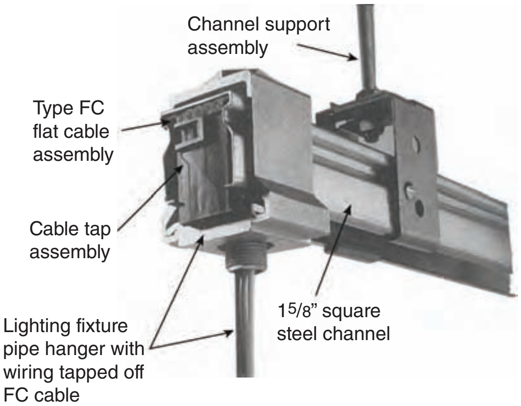


Fig. 28.14 *A 3-phase, 4-wire flat-cable assembly installed in a steel channel is shown. Taps into the conductors are made by tightening the tap device. Taps can be made phase-to-ground to give 120 V and phase-to-phase to give 208 V. (If the cable is connected to a 277/480-V, 3-phase system, then the phase-to-ground and phase-to-phase voltages will be 277 and 480 V, respectively.) After a tap device is removed, the puncture made by the tap "heals" itself. (Courtesy of Chan-L-Wire/Wiremold Company.)*

device being served. In this fashion, lighting fixtures, small motors, unit heaters, and other single-phase, light-duty devices can be served without the necessity of "hard" (conduit and cable) wiring. Figure 28.14 illustrates similar equipment that is specifically intended to feed industrial lighting fixtures.

(c) Lighting Track

This is a factory-assembled channel with conductors for one to four circuits *permanently* installed in the track (*NEC* Article 410-XIV). Power is taken from the track by special tap-off devices that contact the track's electrified conductors and carry the power to the attached lighting fixture, which can be positioned anywhere along the track. The tracks are generally rated at 20 A and, unlike FC cable assemblies, may feed only lighting fixtures. Taps to feed convenience receptacles are not permitted. A typical design is shown in Fig. 28.15. An application of track lighting is shown in Fig. 17.9.

28.16 CABLE TRAY

This system, which is covered in *NEC* Article 392, is simply a continuous open support for approved cables. When used as a general wiring system, the cables must be self-protected. The advantages of this system are free-air-rated cable ampacities, easy installation and maintenance, and relatively low cost. The disadvantages are bulkiness and accessibility requirements. Cable trays are used primarily in industrial applications.

28.17 DESIGN CONSIDERATIONS FOR RACEWAY SYSTEMS

The following sections deal with closed wiring raceways, which completes the discussion of raceways. The details of construction and application are not discussed here because such information is readily available from manufacturers and applicable *NEC*

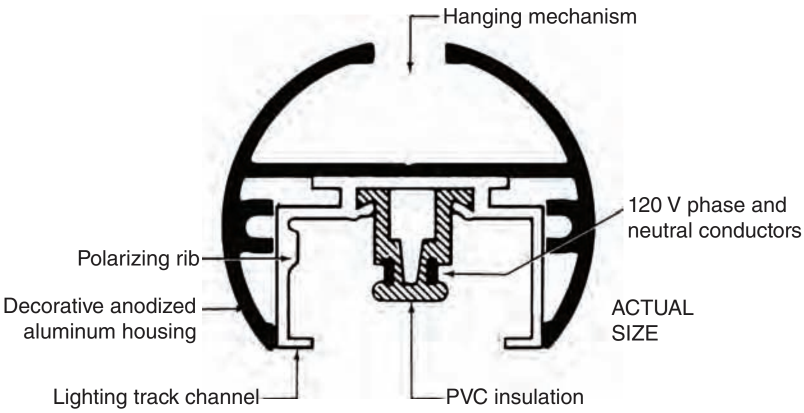


Fig. 28.15 *Decorative lighting track. The circular housing can be obtained in a variety of finishes and hanger arrangements. The actual lighting track, shown full size, is readily available without the housing for direct surface mounting. Track is also available in a 4-conductor configuration (three 120-V conductors plus neutral). (Courtesy of Swivelier.)*

articles. However, enough material is provided for the reader to become familiar with the types of raceways, their common applications and limitations, and, where applicable, comparative characteristics.

Although this chapter covers equipment used primarily in electrical power systems, empty raceways intended for signal, data, and communications wiring (to be provided by others) are normally specified under the electrical section of a construction contract. The function of a raceway in such systems is largely the same as it is for power wiring: protection and isolation of the wiring.

Prior to the widespread use of computers in buildings of all types, raceway space requirements for communication and signal wiring were easily established because such wiring consisted of small telephone cables plus miscellaneous signal and alarm wires. These requirements were readily satisfied with empty conduits or cells in floor raceway systems. Today, when virtually every commercial/institutional building uses some type of data-processing equipment, and communication networking is commonplace even in small facilities, raceways for communication cabling have become a major design consideration. They often far exceed in cross-sectional area the space required for power cabling. Their space requirements are sometimes so great that they, like ductwork, have substantial architectural impact and must therefore be considered early in the design process.

Sizing of raceways for power wiring is an exact process (see Section 29.16), based as it is upon maximum permissible temperatures for specific materials in a given environment. This is not so for communication cabling, even when a system's present requirements are known, because of the extremely rapid growth of demand for networking and data interchange. The problem is all the more difficult when designing commercial space for rental to an unknown client. The advisable approach in such cases is either to provide a reasonable amount of floor-level raceway space for main cabling (see Sections 28.24 and 28.25) and to rely on add-on systems such as under-carpet wiring (see Section 28.29) and surface or ceiling raceways (Section 28.30) for additional raceway area, or, alternatively, to use a structural system that provides virtually unlimited wiring space (Figs. 28.26 through 28.32). Because the latter is a major structural/architectural decision, it must be made during the preliminary stages of design. A clear understanding of the owner's project requirements will assist in decision making.

Design considerations for power system raceways are discussed in the following sections and in Chapter 29. Design of raceways for data and communication system wiring includes the following considerations:

I. Number, type, and location of data-processing terminals
II. Networking requirements:
  A. The type of local area network largely determines the communication media (i.e., coaxial cable, shielded and unshielded wire, and fiber-optic cables), which affects the raceway space requirements. The cable type also determines the type of connectors needed (and their space requirements) and the type of floor outlets used for machine connection.
  B. Cable topology (i.e., interconnection arrangements): This item is frequently not within the domain of the architectural designer, although the raceway space availability seriously affects the cabling arrangement and vice versa.
  C. Requirement for interconnection of networks and connection to remote networks.
III. Number, location, and characteristics of major peripheral devices, such as mass storage, printing, and plotting
IV. Location and type of major subsystems, such as computer-aided design/manufacturing spaces
V. Location of presentation spaces that require interconnection to computer networks

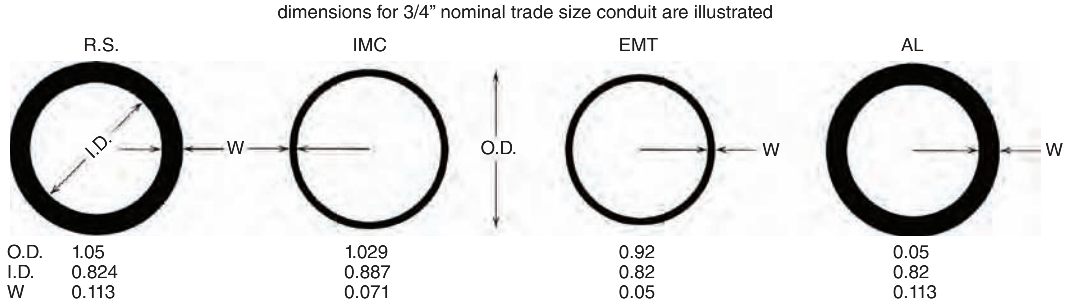
In view of these highly technical and rapidly changing requirements, engaging the services of a consultant with specialization in this area is suggested.

28.18 STEEL CONDUIT

The purpose of conduit is to:

1. Protect the enclosed wiring from mechanical injury and damage from the surrounding atmosphere
2. Provide a grounded metal enclosure for the wiring in order to avoid a shock hazard
3. Provide a system ground path

TABLE 28.7 Comparative Dimensions and Weights of Metallic Conduit[a]



Nominal or Trade Size in. (SI Designation)	Outside Diameter in. (mm)				Inside Diameter in. (mm)				Weight per 10-ft Length (lb)[b]			
	RS[c]	IMC[d]	EMT[e]	AL[f]	RS	IMC	EMT	AL	RS	IMC	EMT	AL
½ (16)	0.84 (21.3)	0.82 (20.8)	0.71 (18.0)	0.84 (21.3)	0.62 (15.8)	0.69 (17.5)	0.62 (15.8)	0.62 (15.8)	7.9 (3.6)	5.3 (2.4)	2.9 (1.3)	2.7 (1.2)
¾ (21)	1.05 (26.7)	1.03 (26.2)	0.92 (23.4)	1.05 (26.7)	0.82 (20.8)	0.89 22.6)	0.82 (20.8)	0.82 (20.8)	10.9 (4.9)	7.2 (3.3)	4.4 (2.0)	3.6 (1.6)
1 (27)	1.32 (33.5)	1.29 (32.8)	1.16 (29.5)	1.32 (33.5)	1.05 (26.7)	1.13 (28.7)	1.05 (26.7)	1.05 (26.7)	16.5 (7.5)	10.6 (4.8)	6.4 (2.9)	5.3 (2.4)
1¼ (35)	1.66 (42.2)	1.64 (41.7)	1.51 (38.4)	1.66 (42.2)	1.38 (35.1)	1.47 (37.3)	1.38 (35.1)	1.38 (35.1)	21.5 (9.8)	14.4 (6.5)	9.5 (4.3)	7.0 (3.2)
1½ (41)	1.90 (48.3)	1.88 (47.8)	1.74 (44.2)	1.90 (48.3)	1.61 (40.9)	1.70 (43.2)	1.61 (40.9)	1.61 (40.9)	25.8 (11.7)	17.7 (8.0)	11.0 (5.0)	8.6 (3.9)
2 (53)	2.38 (60.5)	2.36 (59.9)	2.20 (55.9)	2.38 (60.5)	2.07 (52.6)	2.17 (55.1)	2.07 (52.6)	2.07 (52.6)	35.2 (16.0)	23.6 (10.7)	14.0 (6.4)	11.6 (5.3)
2½ (63)	2.88 (73.2)	2.86 (72.6)	2.88 (73.2)	2.88 (73.2)	2.47 (62.7)	2.61 (66.3)	2.73 (69.3)	2.47 (62.7)	56.7 (25.7)	38.2 (17.3)	20.5 (9.3)	18.3 (8.3)
3 (78)	3.50 (88.9)	3.48 (88.4)	3.50 (88.9)	3.50 (88.9)	3.07 (78.0)	3.23 (82.0)	3.36 (85.3)	3.07 (78.0)	71.4 (32.4)	46.9 (21.3)	25.0 (11.3)	23.9 (10.8)
3½ (91)	4.00 (101.6)	3.97 (100.8)	4.00 (101.6)	4.00 (101.6)	3.55 (90.2)	3.72 (94.5)	3.83 (97.3)	3.55 (90.2)	86.0 (39.0)	54.7 (24.8)	32.5 (14.7)	28.8 (13.1)
4 (103)	4.50 (114.3)	4.47 (113.5)	4.50 (114.3)	— —	4.03 (102.4)	4.21 (106.9)	4.03 (102.4)	— —	97.2 (44.1)	62.5 (28.4)	37.0 (16.8)	— —

[a]Data vary slightly among manufacturers. O.D. is outside diameter; I.D. is inside diameter; W is wall thickness.

[b]Standard length including one coupling; SI weight (in parentheses) given as kg per 3.05 m length.

[c]Standard heavy-wall rigid steel conduit.

[d]Intermediate-weight steel conduit.

[e]Electric metallic tubing.

[f]Aluminum conduit.

4. Protect surroundings against a fire hazard as a result of overheating or arcing of the enclosed conductors
5. Support the conductors

For these reasons, the *NEC* generally requires that all power wiring be enclosed in a rigid metallic corrosion-resistant conduit. To this latter end, steel conduit is manufactured in several types, among which are hot-dip galvanized, sherardized (coated with zinc dust), enameled, and plastic-covered.

There are three types of steel conduit that differ basically only in wall thickness. They are, in order of decreasing weight:

1. Heavy-wall steel conduit, also referred to simply as *rigid steel conduit*; covered by *NEC* Article 344
2. Intermediate metal conduit, usually referred to as *IMC*; covered by *NEC* Article 342
3. Electric metallic tubing, normally known as *EMT* or *thin-wall conduit*; covered by *NEC* Article 358

The differences are shown in Table 28.7. Several types of conduit (including rigid steel) are shown in Fig. 28.16. The equivalent SI dimensions of conduits are given in Table 28.8.

Rigid conduit and IMC use the same threaded fittings. As a result of its thin wall, EMT is not threaded; instead, it uses set-screw and pressure fittings. The thinner walls of EMT and IMC yield a larger inside diameter (ID) and, therefore, easier wire pulling. The combination of lower weight and easier wire pulling gives EMT and IMC a distinct labor-cost advantage over rigid conduit, which is further enhanced in jobs with a great deal of field bending and handling of conduit. Both, however, have application restrictions, which are detailed in the *NEC*.

Generally, no conduit smaller than ½-in. (13-mm) nominal trade diameter is used. Ordinary steel pipe may not be used as electric conduit, and all electric steel conduit is distinctively marked as such.

When steel conduit is installed in direct contact with the earth, it is advisable to use the hot-dip galvanized type and to coat the joints with asphaltum. If the earth is very wet, the entire conduit system should be coated with an appropriate waterproofing compound. Alternatively, a plastic-jacketed conduit can be used.

Conduit is fastened to the building structure in much the same way as piping: with pipe straps and clamps. The vertical load at floor openings is taken with special support clamps. Trapeze mounting is common for conduit banks hung from the ceiling, as in Fig. 28.17.

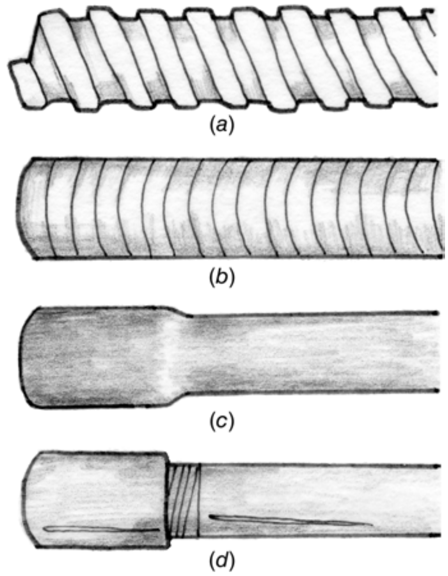


Fig. 28.16 *Conduits: (a) flexible aluminum conduit, suitable for power and lighting circuits, (b) flexible steel, liquid-tight conduit, resistant to moisture, oil, and sunlight, (c) polyvinyl chloride (PVC) conduit, resistant to heat and corrosion, (d) galvanized steel conduit, protects against magnetic fields and damage to electrical cables. (Drawing by Karen Tse; © Alison Kwok, all rights reserved)*

TABLE 28.8 SI Equivalents of Rigid Steel Conduit Sizes

		Dimensions mm		
Conduit Size in.	**SI Designation**	**Outside Diameter**	**Inside Diameter**	**Wall Thickness**
½	16	21.3	16.1	2.6
¾	21	26.7	21.3	2.7
1	27	33.4	27.0	3.2
1¼	35	42.2	35.4	3.4
1½	41	48.3	41.3	3.5
2	53	60.3	52.9	3.7
2½	63	73.0	63.2	4.9
3	78	88.9	78.5	5.2
3½	91	101.6	90.6	5.5
4	103	114.3	102.9	5.7

Source: www.steelconduit.org/

Conduit size depends not only on the maximum permissible temperature of the contained conductors, but also on the number and diameter of the wires that may be drawn into the conduit without injuring the wire. The number and radius of bends in the conduit, as well as its total length, affect the degree of abrasion to the wiring insulation during installation. No wires should be installed until a conduit system has been inspected and approved.

For structural reasons, conduits in concrete slabs are run close to the bottom surface (in the portion of the slab in tension) or near the center. If a large number of conduits must be embedded, it may be necessary to increase the slab thickness. In many instances, the structural slab is covered with a concrete topping, in which conduit may be installed without affecting slab integrity. In all cases, local building codes should be consulted for limitations on embedded conduits. In any event, the top of any conduit shall be at least ¾ in. (19 mm) below the finished floor surface to prevent cracking. When heavy trucking is expected, this allowance should be increased to 1½ in. (38 mm) minimum.

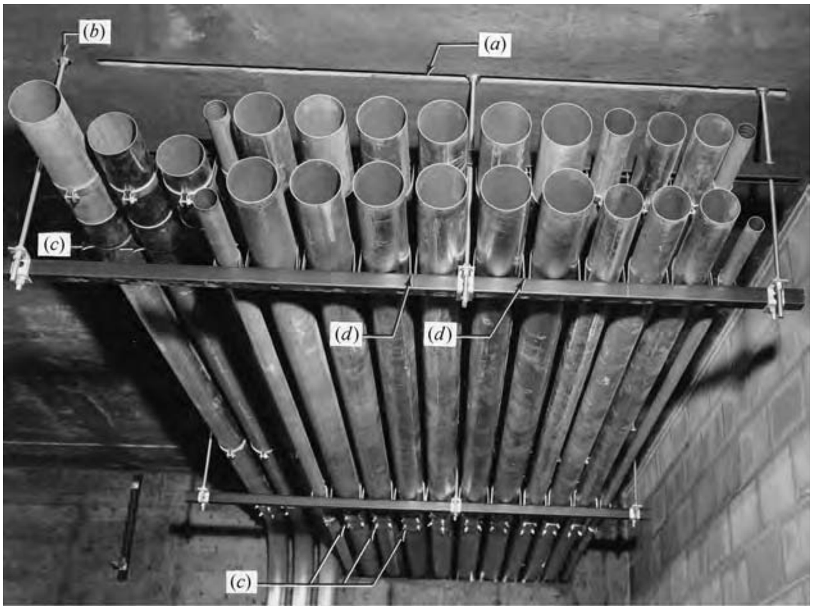


Fig. 28.17 *Typical overhead conduit bank installation. Note that due to field conditions the insert (a) for hanger rods was inadequate and an additional rod (b) was provided. This conduit bank uses EMT, which has a pipe-wall thickness approximately one-third that of heavy-wall rigid conduit. The resulting weight difference in a large bank such as this is very pronounced. EMT joints are made with set-screw fittings (c). Note how individual conduits are fixed by clamps to the trapeze channel (d). (Courtesy of Republic Steel Corp.)*

In general, the following rules should be observed and included in all specifications for conduit work in concrete slabs:

1. Conduits shall have an outside diameter (OD) no greater than one-third the slab thickness, as measured at its thinnest point.
2. Conduits running parallel to each other shall be spaced not less than three times the OD of the largest conduit center-to-center.
3. Conduit crossings shall be as close to a right angle as possible.
4. Minimum cover over conduits shall be ¾ in. (19 mm).

28.19 ALUMINUM CONDUIT

The use of aluminum conduit has increased greatly in recent years because of the weight advantage that aluminum has over steel, being even lighter than EMT. The savings in labor costs usually more than offset the additional cost of the material itself. In addition, aluminum has better corrosion resistance in most atmospheres; it is nonmagnetic, giving a lower voltage drop; it is nonsparking; and, generally, it does not require painting.

Its major drawback is its deleterious effect on many types of concrete, causing spalling and cracking when embedded. Although manufacturers can demonstrate cases of embedding in concrete without harmful effect, this procedure should be avoided unless the concrete additives are rigidly controlled and the conduit is coated to prevent contact with the concrete. It is also inadvisable to bury aluminum in earth, with or without asphalt or another coating, because of the rapid corrosion often encountered. Other difficulties frequently encountered are mechanical freezing of threaded joints (because of thread deformation) and difficulty in obtaining electrical contact with grounding straps. With the exceptions noted, aluminum conduit may be used in all locations where steel conduit is used.

28.20 FLEXIBLE METAL CONDUIT

This type of conduit consists of an empty, spirally wound, interlocked armor steel or aluminum raceway. It is known to the trade as *Greenfield* and is covered in *NEC* Article 348. It is used principally for motor connections and other locations where vibration is present, where movement is encountered, or

Fig. 28.18 *This is a good application for liquid-tight, flexible conduit because it provides weatherproofing and mechanical isolation of the vibration-producing equipment. (Courtesy of Electri-Flex Company.)*

where physical obstructions make its use necessary. The vibration isolation provided by flexible conduit is one of its most important applications. It should always be used in connections to motors, transformers, ballasts, and the like. Another common application is for wiring inside metal partitions. When covered with a liquid-tight plastic jacket, it is suitable for use in wet locations (Fig. 28.18). In this configuration, it is most often known by the trade name *Sealtite*.

28.21 NONMETALLIC CONDUIT

A separate classification of rigid conduit (addressed by several *NEC* Articles) covers raceways that are formed from such materials as fiber, asbestos–cement (not as serious an environmental concern as it might sound), soapstone, rigid polyvinyl chloride (PVC), and high-density polyethylene.

For use aboveground, such conduit must be flame-retardant, tough, and resistant to heat distortion, sunlight, and low-temperature effects. For use underground, the last two requirements are waived. Generally, nonmetallic conduit may be used without restriction in nonhazardous areas within the physical limitations of the material involved. Thus, plastic conduit has a temperature limitation, asbestos–cement has considerable physical strength limitations, and so on. As a result of these limitations, PVC conduit is the material of choice for indoor exposed use, and asbestos–cement, fiber, and PVC plastic for outdoor and underground use. A separate ground wire *must* be provided because the ground provided by a metallic conduit is absent.

28.22 SURFACE RACEWAYS (METALLIC AND NONMETALLIC)

These raceways are covered in *NEC* Articles 386 and 388. Surface raceways and multioutlet assemblies may be utilized only in dry, nonhazardous, noncorrosive locations and may generally contain only wiring operating below 300 V. Such raceways are normally installed exposed, in places not subject to physical injury.

The principal applications of surface raceways are:

1. Where economy in construction weighs very heavily in favor of surface raceways and where expansion is anticipated (Fig. 28.19)
2. Where outlets are required at frequent intervals and where rewiring is required or anticipated (Figs. 28.20)
3. Where access to equipment in the raceways is required and/or where necessary due to the nature of the wiring (Figs. 28.19, 28.21, 28.22, and 28.23)

Fig. 28.19 *Multi-section nonmetallic surface-type raceway measures 4 in. H and 1.5 in. D (100 × 38 mm). The sections are intended for power, telephone, and data cabling. The outlet box protrudes from the raceway surface so as not to lessen the raceway wiring space. Vertical dividers in the raceway keep the three distinctly different types of wiring completely separated. (Photo courtesy of Hubbell, Inc.)*

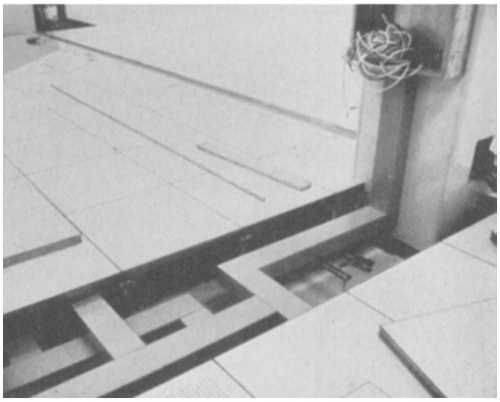


Fig. 28.20 *Large-capacity surface metal raceways are particularly useful for wiring in full-access floors (see Section 28.28) because of the heavy wiring (see wall box) and frequent rewiring. The perforated floor tile in the foreground is used to supply laminar airflow in this clean room at an integrated circuit manufacturer's facility.*

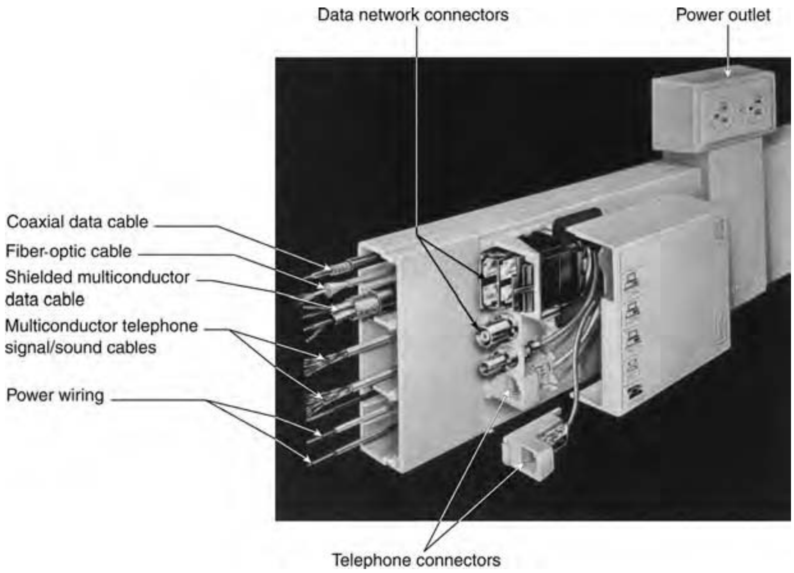


Fig. 28.21 *Multichannel nonmetallic surface raceway with snap-in connector modules for data network, signal, and power wiring systems. (Similar metallic raceways are also available.) The raceway itself measures 4½ in. H × 1 in. D (115 × 25 mm). The internal dividers are movable or entirely removable, which permits varying the number and size of the wiring channels. The principal application of this type of wireway is in commercial occupancies using extensive desktop data-processing and communication equipment. (Courtesy of Panduit.)*

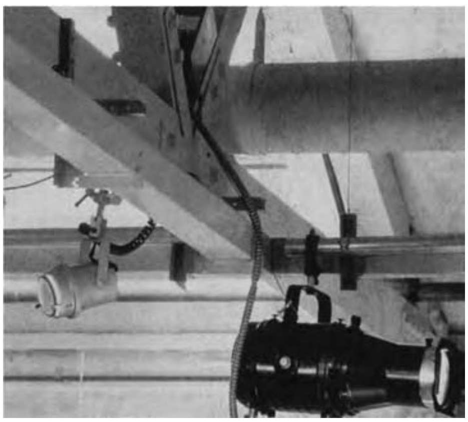


Fig. 28.22 *The frequent wiring changes required for theater and exhibition lighting are easily made when the wiring is run in a suspended surface raceway.*

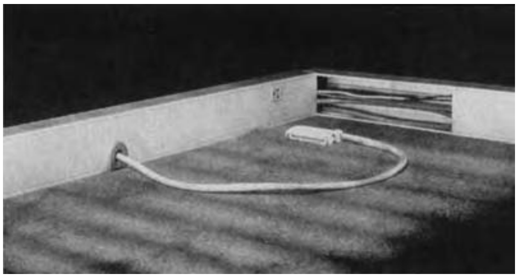


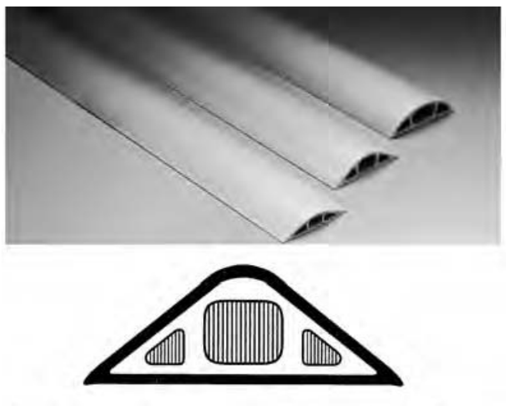
Fig. 28.23 *The basic raceway illustrated is $1\frac{7}{8}$ in. D × $3\frac{3}{16}$ in. W (48 × 81 mm). It is shown with a divider installed, permitting use of the top section for power wiring and the bottom section for low-voltage wiring. Because data and communication cables are frequently supplied with factory-installed terminations (as in the photo), a raceway where the cable can be laid in rather than pulled in is required. Also, terminal strips and other equipment can be installed in the low-voltage section of these large raceways, making the use of separate terminal cabinets unnecessary.*

4. Where the extensive and expensive cutting and patching required to "bury" a raceway during rewiring is to be avoided (Fig. 28.24)

28.23 OUTLET AND DEVICE BOXES

These boxes are generally of galvanized stamped sheet metal. The most common sizes are the 4-in. (100-mm) square and 4-in. (100-mm) octagonal boxes used for fixtures, junctions, and devices and the 4 × $2\frac{1}{8}$ in. (100 × 54 mm) box used for single devices where no splicing is required. Box depths vary from $1\frac{1}{2}$ to 3 in. (38 to 76 mm). Nonmetallic boxes may be used with NM and NMC cable and with nonmetallic conduit installations. In wet locations and for outdoor work, cast-iron or cast-aluminum boxes are recommended.

An *NEC* (Article 300–21) requirement that electrical penetrations in fire-rated floors be designed to maintain fire ratings has spurred electrical manufacturers to produce a line of poke-through fittings to meet this need. (This requirement applies also to rated walls, ceilings, and partitions.) One such design is shown in Fig. 28.25. These electrical penetrations have become increasingly prevalent in existing commercial spaces where the expanded need for desktop power and data wiring can be met most economically and rapidly by through-the-floor



FloorTrak	2	3	4
Width	2.68"	2.985"	2.975"
Height	.465"	.610"	.885"
Ctr. Hole	.50x.312"	.75x.500"	1.0x.750"

Fig. 28.24 *Where low-voltage wire and cable cannot be concealed (buried), shallow, properly shaped floor track can be used. Such installations should avoid foot-traffic areas, where possible, to minimize trip hazards. (Courtesy of Hubbell Premise Wiring.)*

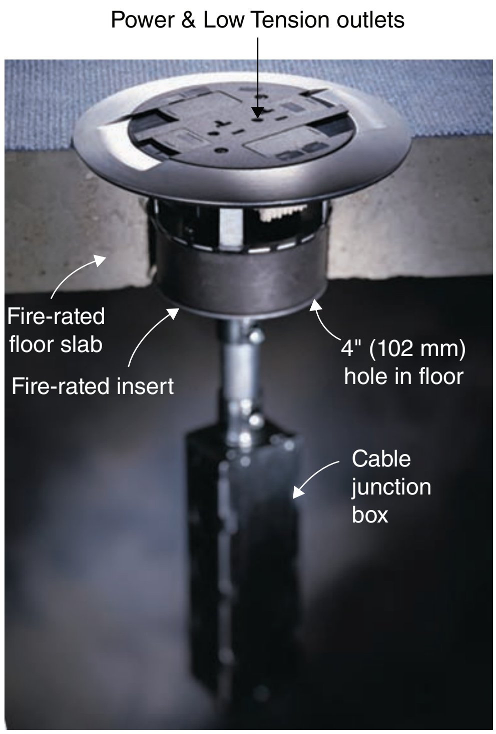


Fig. 28.25 *Typical poke-through electrical fitting mounts in a 4-in. (100-mm) hole. It is wired from underneath with the required power, telephone, signal, and data cables. Power and low-voltage cables are separated as required by code. Units are available prewired or suitable for field wiring, and adaptable for varying floor thicknesses. The floor fitting is provided with power, telephone, and data cable outlets as required for the specific installation.*

feeds from accessible wiring in the suspended ceiling plenum below. In addition, these fittings facilitate the electrical wiring relocations so common in rental office occupancies.

28.24 FLOOR RACEWAYS

In commercial spaces with large open floor areas, it is common practice to place desks and other workstations throughout the space, at considerable distances from permanent walls containing electrical services. Because each workstation in a modern office requires electric power for a computer, desk lamp, and other common equipment plus a telephone line, a computer network connection, and possibly a data outlet, the problem of bringing these services to the workstations with a minimum of exposed wiring is challenging. The required outlets can be installed on the floor adjacent to or under the workstations or, if partial-height partitions are used, within these partitions.

To bring the various electrical and communication services to the user, in the absence of a well-designed overall floor raceway system, the installing contractor has one of four choices:

1. Channel the floor and install a conduit in the channel, connecting it to the nearest wall outlet. Patch the chased portion of the floor.
2. Install a surface floor raceway. The usefulness of this technique is very limited because it presents a tripping hazard and problems with routine floor cleaning.
3. Drill through the floor twice and connect the new outlet to a nearby existing floor or wall outlet via a conduit on the underside of the floor slab. Floor penetrations must be fireproof.
4. Drill through the floor and run a conduit in or on the ceiling below. For using this technique, special poke-through fittings are available that restore the fire rating of the slab (see Fig. 28.25). These fittings are designed to carry all the electric services normally required at a workstation. They can then be connected to a single-location multiservice floor outlet group, as in Fig. 28.25, or used to wire the partitions in a workstation, as in Fig. 28.26.

All four of these methods have serious disadvantages; method 1 is labor intensive, method 2 is unsightly and presents a safety hazard, methods 3 and 4 disturb the occupants below, and all four methods are generally inflexible and therefore unsuitable for spaces where reasonable changes in wiring and workstation location are anticipated. For these reasons, overall-access in-floor and underfloor raceway systems were developed and are widely used in high-grade commercial and institutional spaces.

The *NEC* recognizes three types of in-floor raceways:

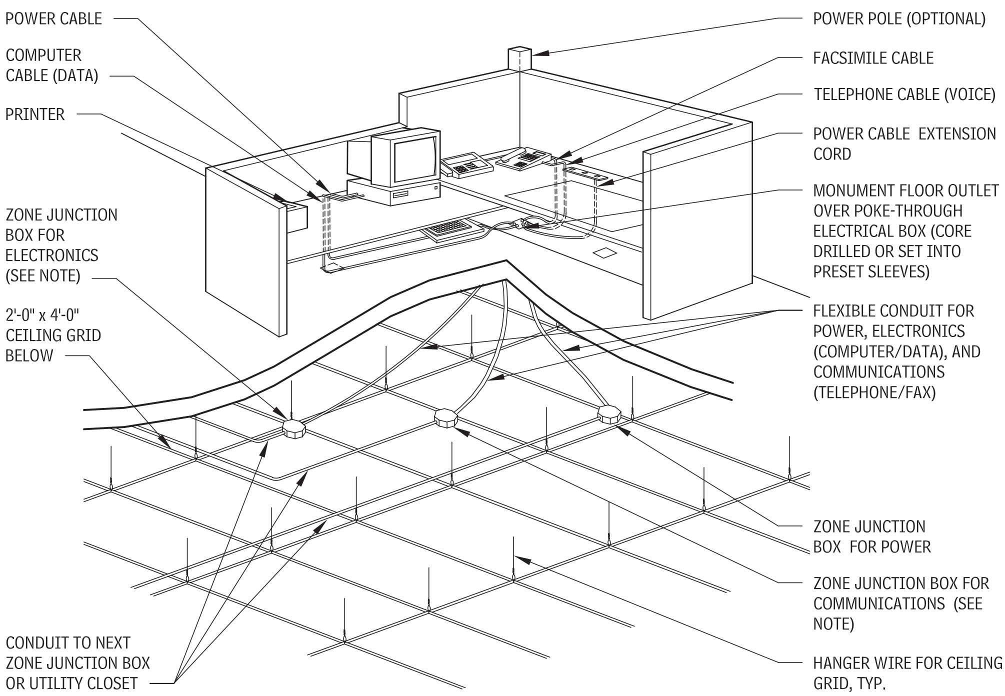
Underfloor raceways—Article 390
Cellular metal floor raceways—Article 374
Cellular concrete floor raceways—Article 372

All three types are applicable to a wide range of structures, and none may be used in corrosive or hazardous areas. The fundamental difference between them is that underfloor raceways are added onto the structure, whereas cellular floor raceways are part of the structure itself—and therefore have a pronounced effect on architectural coordination. (Underfloor duct systems antedate poke-through fittings, which are a relatively recent development.)

28.25 UNDERFLOOR DUCT

These raceways may be installed beneath or flush with the floor. They find their widest application in office spaces because their use permits placement of power, data, and signal outlets close to desks and other furniture, regardless of spatial layout. Underfloor duct systems were widely employed until the introduction of what may be called *over-the-ceiling* ducts (in contrast to under-the-floor ducts) and flat-cable under-carpet wiring. These systems are discussed in Sections 28.29 and 28.30. The reason that alternative systems were developed is simply economic: underfloor duct systems are expensive and, because they are inflexible, being literally cast in concrete, they are frequently underutilized in one area while being inadequate in another. Before discussing the relative merits of systems, however, an understanding of what underfloor duct systems are and how they are assembled and utilized is necessary.

An underfloor duct system is simply an arrangement of parallel rectangular metal or heavy plastic raceways laid on the structural slab and



DESK EQUIPMENT LAYOUT

Computer and telephone cabling is often combined as an integrated voice/data cabling system, eliminating the need for three raceways, except when extra capacity is needed.

Fig. 28.26 *Typical application of a through-the-floor system to provide power, telephone, and data service to a modern workstation. This drawing shows the electrical services being tapped at junction boxes in a hung ceiling conduit system on the floor below. The ceiling wiring system can also be a raceway network in lieu of the hard-wiring shown here. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards*, 11th ed. 2007. Reprinted by permission of John Wiley & Sons.)*

covered with concrete fill. Access to the wiring in these *distribution ducts* is via inserts that connect to openings in the ducts and terminate in floor fittings for both power and signal/data wiring. Cable feeds to the distribution ducts are supplied by a second set of rectangular raceways called *feeder ducts*, usually laid at right angles to the distribution ducts.

In a *single-level* underfloor duct system, the distribution and feeder ducts are on the same level, and the interwiring between them is accomplished in junction boxes. The advantage of a single-level system is shallow concrete fill, normally 2½ to 3 in. (64 to 76 mm). The limiting constraint of a single-level system is the junction box, which becomes more complex and multisectioned with an increasing number of ducts and wires. Newer systems utilize a one-piece triple-cell duct for both distribution and feeder ducts, with factory set inserts every 24 in. (610 mm) that straddle all three cells at once (Fig. 28.27). By placing distribution ducts on 5-ft (1.5-m) centers with adequate crosswise feeder ducts and utilizing large flat junction boxes, a cost-effective installation adequate for all but the heaviest wiring demands can be assembled. For demanding areas, distribution ducts can be arranged to feed under-carpet cables (see Section 28.29).

Because the initial cost of a full underfloor system is high, an alternative arrangement utilizes *only* feeder ducts on approximately 25-ft (7.6-m) centers, with flat (under-carpet) cable box connectors spaced approximately every 20 ft (6.1 m) along the feeder ducts. The low-tension (voltage) portion of this system relies completely on flat telephone and data transmission cables, including fiber-optic (FO) cables. Because these cables are generally precut and factory terminated, the system requirements must be carefully analyzed (see Section 28.29) before committing to a complete under-carpet wiring system.

A two-level underfloor duct system is essentially the same as a single-level system except that

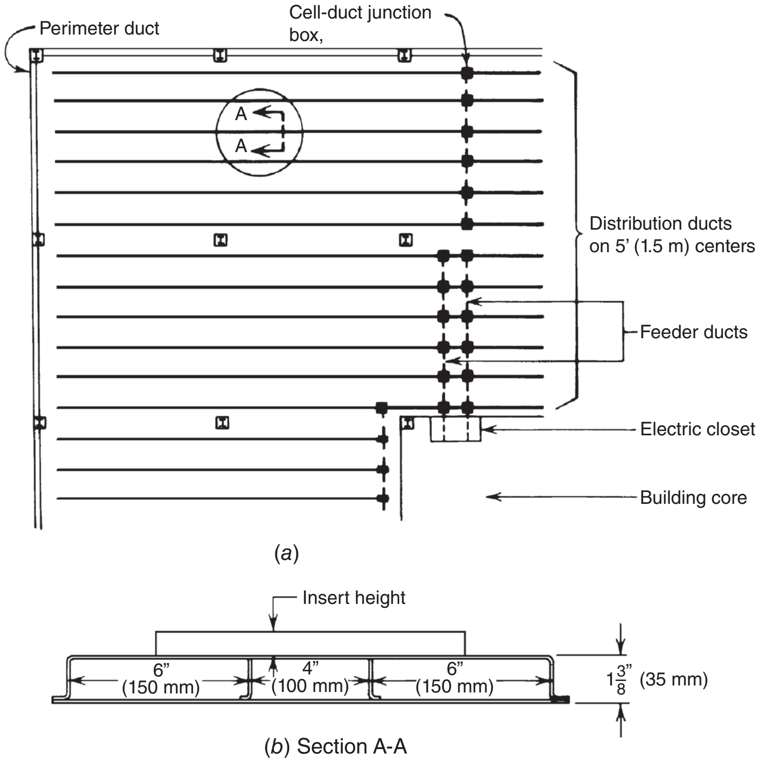


Fig. 28.27 *Details of a single-level underfloor duct system utilizing three-section cell duct for both distribution and feeder ducts. (a) Portion of a typical large open floor space in a commercial facility. Distribution ducts may be placed as close as 5-ft (1.5-m) on-center to satisfy dense desk spacing. (b) Three-cell distribution duct utilizes a 4-in.- (100-mm)-wide center cell (4.9 in.^{2} [3160 mm^2]) for power and either 3-in.- (75-mm)-wide (3.7 in.^{2} [2386 mm^2]) or 6-in.- (150-mm)-wide (7.4 in.^{2} [4773 mm^2]) outer cells for signal and data cabling. Minimum concrete fill depth is 2½ in. (64 mm), resulting in a minimum 1-in. (25-mm) cover over the distribution ducts. Service fittings are flush with the floor. (Courtesy of Square D Company.)*

the distribution ducts and feeder ducts are on different levels (Fig. 28.28). This arrangement has the advantages of simplifying junction boxes and of giving the system unlimited feeder capacity, but the distinct disadvantage of requiring a minimum of 3⅝ in. (92 mm) of concrete fill. This additional slab thickness can frequently be avoided by depressing part of the slab to accommodate feeder ducts run *under* the distribution ducts, as shown in Fig. 28.29.

A typical two-level system is illustrated in Fig. 28.30. Here, the feeder ducts run above the

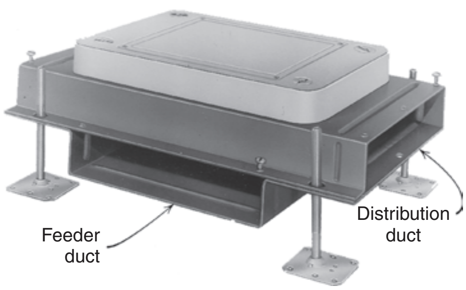


Fig. 28.28 *Typical two-level junction box demonstrates the simplicity of the two-level system. (Courtesy of Square D Company.)*

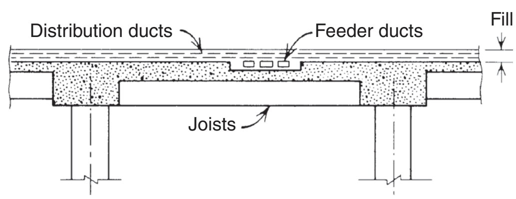


Fig. 28.29 *Setting a two-level underfloor duct system. To avoid thickening the fill, a depression in the slab can accept feeder ducts. Ducts would be run near the bay center to avoid the negative steel required of joists near columns.*

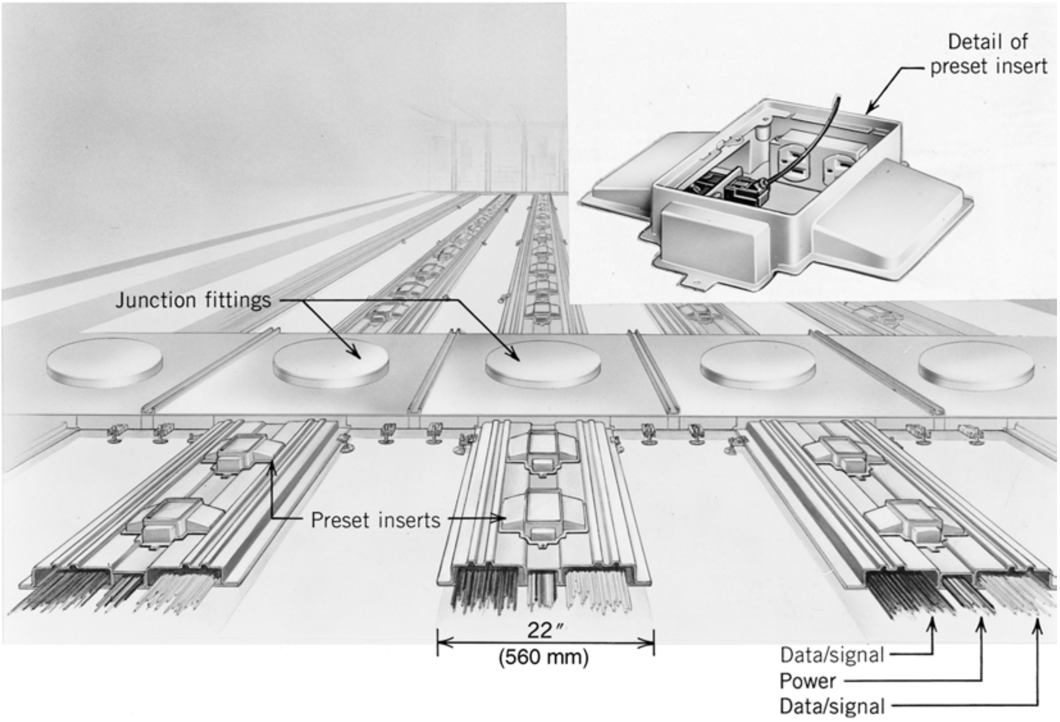


Fig. 28.30 *Modified two-level underfloor duct system requires 3 in. (75 mm) of concrete fill for 2-in.- (50-mm)-high ducts and 4 in. (100 mm) of fill for 3-in. (75-mm)-high ducts. Preset inserts (see detail) straddle all three cells and provide two duplex power receptacles plus connection to both low-voltage cells. Distribution ducts recess into feeder-header ducts at junction boxes to reduce the overall height. (Photo courtesy of Walker Systems, A Division of The Wiremold Company.)*

distribution ducts and intersect at a specially constructed junction fitting, into which the distribution ducts partially recess in order to reduce overall system height. The required concrete fill is either 3 or 4 in. (75 or 100 mm), depending upon the depth of the distribution cells (2 or 3 in. [50 or 75 mm]).

In all underfloor duct systems, the principal cable capacity bottleneck is usually the supply point to the *feeder* ducts. One solution to this problem uses a special feed arrangement at panels (Fig. 28.31). Another possibility is to subdivide large floor areas, supplying each via a system of multiple feed points arranged in closets or at wall panels. In such systems, care must be taken to ensure sufficient interconnection capacity between feed points because data networks are not only floorwide but frequently buildingwide.

Underfloor ducts may be cast into the structural slab in lieu of being installed in fill or topping, but the slab must be designed to accommodate them. The use of a fill or topping on the structural slab for an underfloor duct installation has these advantages:

1. Ducts can be run in any direction, without conflict with structural elements.
2. Finishing is simplified.
3. Coordination is simplified.
4. Formwork and construction sequence are simplified.

The disadvantages are:

1. Additional concrete increases costs directly by increasing the weight of the structure. This is particularly expensive in seismic designs.
2. The building height may be increased.

In retrofit jobs where underfloor duct is selected rather than one of the other floor or ceiling raceway systems, the ducts will be placed in a new (added) floor fill.

In conclusion, some general comments on the application of underfloor duct systems are in order.

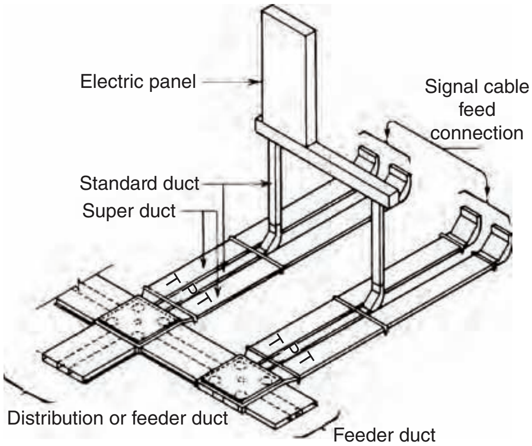


Fig. 28.31 *Due to the large capacity of both distribution ducts and feeder ducts, central cable feed points—at electric closets, for instance—can cause bottlenecks. Illustrated is one possible solution, consisting of a double-duct feed arrangement. Signal cable would feed in from cable boxes (not shown). P is a power duct, T a signal duct. (Diagram courtesy of Square D Company.)*

Underfloor duct systems are *expensive*. They can add 50% to the building's electric system cost, without consideration of the other construction costs involved. To justify their use, therefore, a building should meet these criteria:

1. There are open floor areas, with a requirement for outlets at locations removed from walls and partitions.
2. An under-carpet wiring system is inapplicable.
3. Outlets from ceiling systems are unacceptable.
4. Frequent rearrangement of furniture and other items requiring electrical and signal service is anticipated.

The facilities that may meet these criteria include many office buildings, museums, galleries (and other display-case spaces), high-cost merchandising areas, and selected areas in industrial facilities. Bear in mind that even in high-cost office construction, underfloor duct systems are difficult to justify economically unless the spatial/furniture layout will be likely to change. In doubtful cases, alternate arrangements can be planned and an intelligent choice made after costs and the impact on the building structure are studied.

28.26 CELLULAR METAL FLOOR RACEWAY

The underfloor duct system described previously is best applied to rectilinear arrangements. More free-flowing arrangements, such as those found in office landscaping layouts, require a fully accessible floor—if the floor is to be used for electrification. This may be provided by a cellular (metal) floor that is an integrated structural/electrical system. The floor can be partially or completely electrified. One of the many available structural element approaches is shown in Fig. 28.32.

The cellular floor is part of the structural system and is designed accordingly. Electrical wiring is fed into the cells from header ducts and/or trenches that run perpendicular to the floor cells and constitute a system of underfloor ducts in themselves. The header ducts in turn are fed from electric panels and signal, data-transmission, and telephone cabinets in much the same manner as underfloor ducts are fed.

Three types of wiring systems generally run in separate floor cells and header ducts—electric power, data-transmission wiring, and telephone and signal systems. The last two may be combined in a single cell only if the signal system voltage and power level are low and the local telephone company approves. A complete range of outlets and fittings is available.

28.27 PRECAST CELLULAR CONCRETE FLOOR RACEWAYS

This structural concrete system is similar to a cellular metal floor in application and has the same advantages: large capacity, versatility in that each cell is a potential raceway, and flexibility in outlet placement and movement. Here too, as with metal cell constructions, the first cost is higher than that of standard underfloor duct installation, although the life-cycle cost is frequently lower, depending upon space use and reconfigurations.

A cell is defined in *NEC* Article 372 as a "single, enclosed tubular space in a floor made of precast cellular concrete slabs, the direction of the cell being parallel to the direction of the floor member." A feed for these cells is provided, as with metal cellular floor construction, by header ducts. Although header ducts are normally installed in concrete

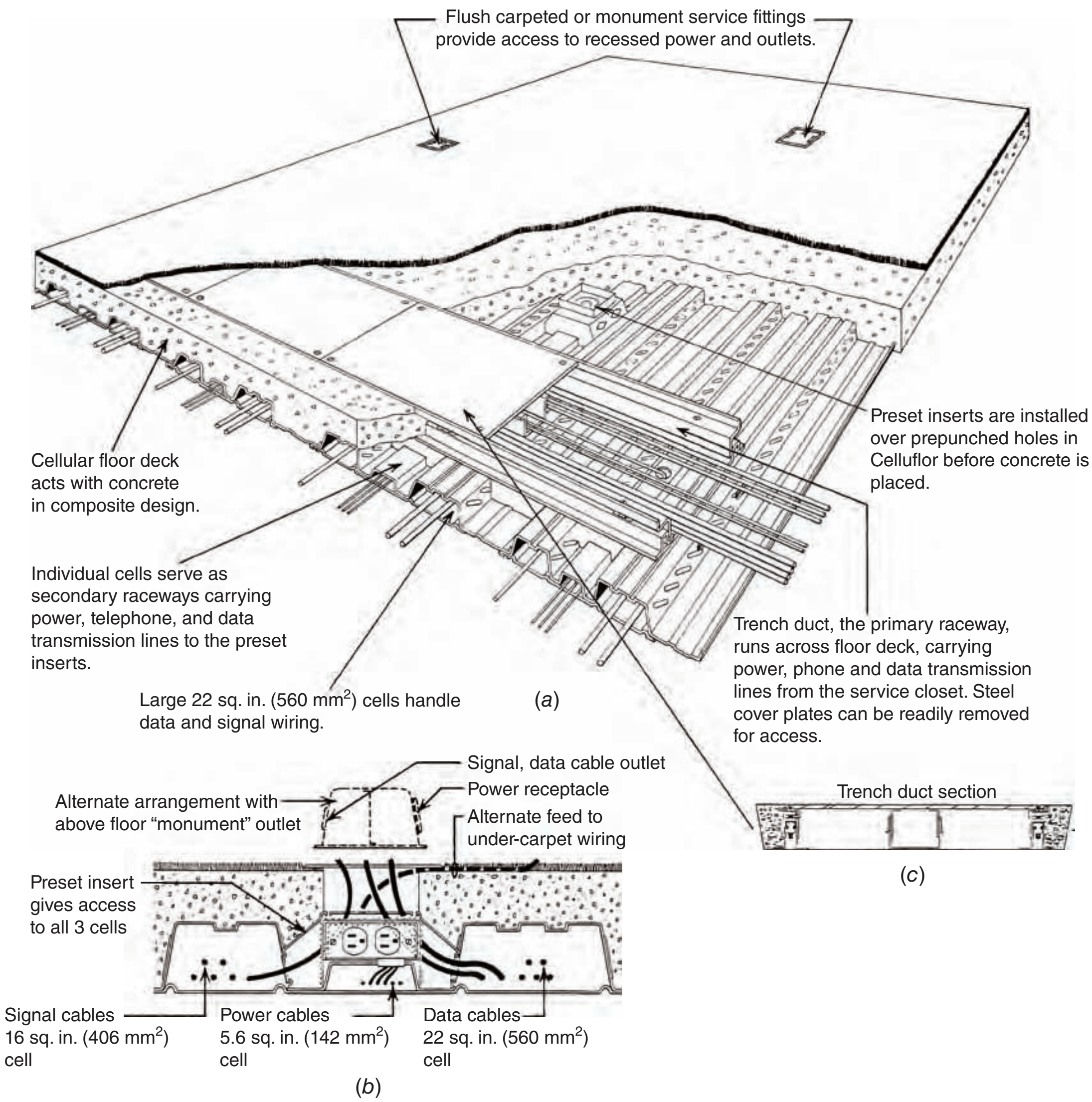


Fig. 28.32 *(a) One of several options for electrified cellular floors. The floor cells are available in many designs, depending primarily upon the structural requirements. The trench (illustrated in c) that straddles the cells provides the electrical feeds through precut holes in the cells. The trench itself is completely accessible from the top and, when opened, exposes all the wiring and the cells below. (b) Activated preset insert. Note that the insert straddles the center (power) cell and provides access to the two adjoining low-voltage wiring cells. Power and signal wiring are completely separated at all times by metal barriers. If desired, a standard surface "monument" fitting can be mounted on the floor, or a connection can be made to under-carpet cables in lieu of the flush plate shown. When an insert is to be deactivated, the flush cover plate is simply replaced with a blank plate. (c) Section through a trench duct, which acts as a feeder for distribution ducts. The trench is available with or without bottom, in any required height, in widths from 9 to 36 in. (230 to 915 mm), and one, two, or three compartments, depending upon floor cell design and cabling requirements. (Photo courtesy of Walker Systems, A Division of The Wiremold Company.)*

fill above the hollow-core structural slab, a header arrangement with feed from the ceiling below is also entirely practical. As with a metallic cellular floor, the cells can be used for air distribution and even for piping, although these elements are generally installed in a hung ceiling.

28.28 FULL-ACCESS FLOOR

This construction is applicable to spaces with very heavy cabling requirements, particularly if frequent recabling and reconnection are required. It provides rapid and complete access to an underfloor plenum. The system was originally developed for data-processing areas that require large, fully accessible cable spaces and large quantities of conditioned air. The solution to both of these requirements is an infinite-access floor, usually constructed of lightweight die-cast aluminum panels supported on a network of adjustable steel or aluminum pedestals. Panels are available from 18 × 18 in. to 36 × 36 in. (457 × 457 mm to 915 × 915 mm), and floor depth is normally 12 to 24 in. (305 to 610 mm), although taller pedestals are available. The subfloor space thus created can be used for cabling and also to carry conditioned air either in ducts or by using the entire space as an air plenum. (In the latter case, the wiring system must be suitable for air plenum use; as in Fig. 28.20.) The construction is usually fireproof. Sufficient floor-to-floor height is necessary to accommodate the raised floor. This approach to electrical distribution may coordinate quite well with an underfloor air distribution system (UFAD)—see Chapter 12.

Where air requirements are limited or nonexistent and the floor is intended primarily for cabling, pedestals as short as 6 in. (152 mm) can be used, thus reducing ceiling height problems (Fig. 28.33). In such access floor spaces, use of multiservice distribution modules and modular wiring avoids cable tangles and reduces labor costs significantly (Figs. 28.33, 28.34, 28.35, 28.36).

28.29 UNDER-CARPET WIRING SYSTEM

This system, which is covered in *NEC* Article 324, was originally developed as both an inexpensive alternative to an underfloor or cellular floor system and as a means for providing a flexible floor-level branch circuit wiring system. Essentially, the system

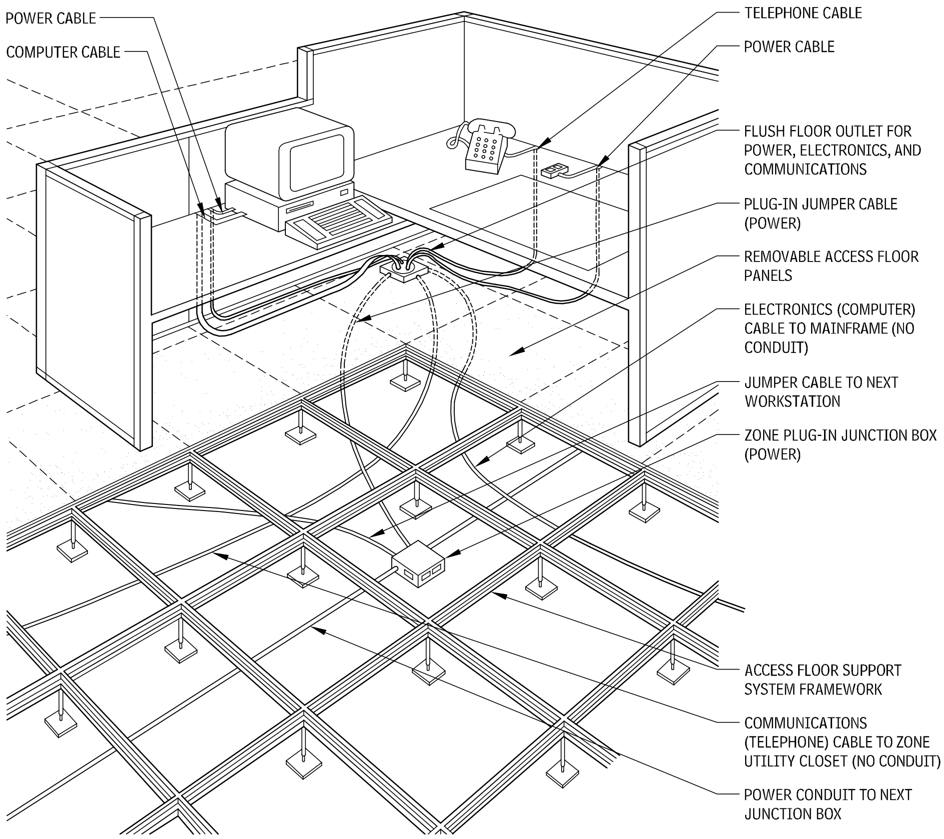


Fig. 28.33 *Pictorial representation of a full-access floor designed to provide complete electrical, data, and signal services to a modern workstation layout. The infinite access and unlimited space are ideal for heavily wired, rapidly changing workstation arrangements. (From AIA: Ramsey/Sleeper,* Architectural Graphic Standards, *11th ed. 2007. Reprinted by permission of John Wiley & Sons.)*

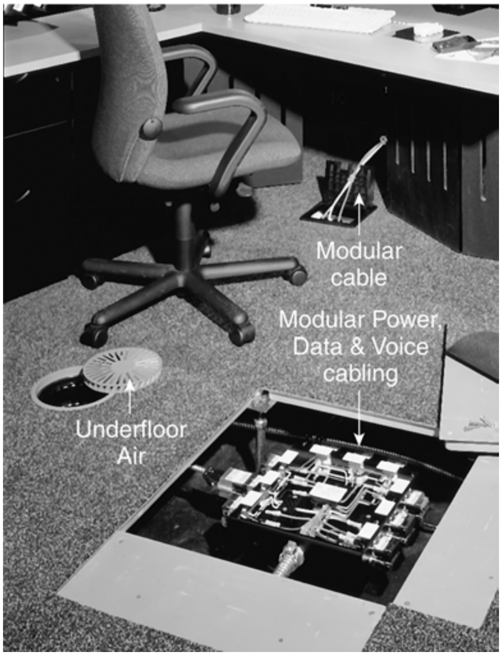


Fig. 28.34 *Full-access floors provide infinite access to the myriad cables used in a modern commercial office. The modular wiring, using snap-on connectors and preassembled junction boxes (see Fig. 28.36a), drastically reduces the labor cost of installation and frequent cabling changes. (Photo courtesy of Tate Access Floors, Inc.)*

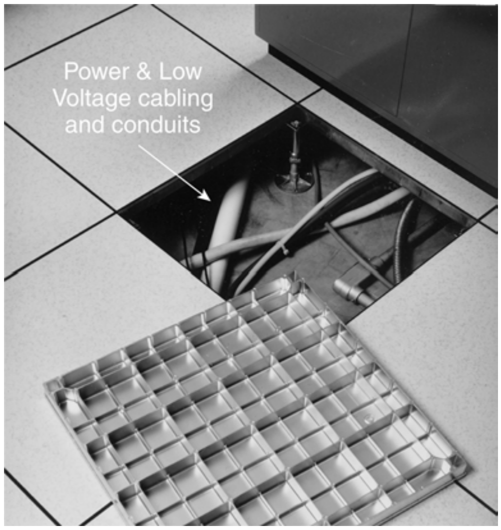
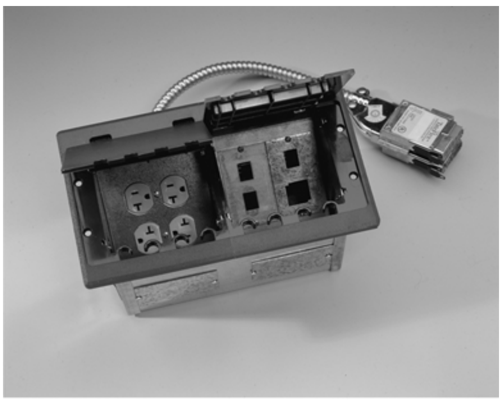
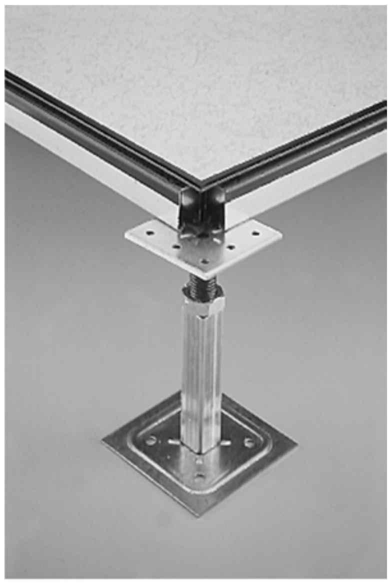


Fig. 28.35 *Reinforced nonferrous (aluminum) floors are used frequently in hi-tech applications requiring the large wiring capacity and convenience of full-access floors. Floor construction can be stringerless, as illustrated, or with stringers, as in Fig. 28.36b. (Photo courtesy of Tate Access Floors, Inc.)*



(*a*)



(*b*)

Fig. 28.36 *(a) Typical power/low-voltage floor box for use with a full-access floor. (b) Steel-bolted stringer support for access floor panels. Many stringer and stringerless designs are available (see Fig. 28.35). (Photos courtesy of Tate Access Floors, Inc.)*

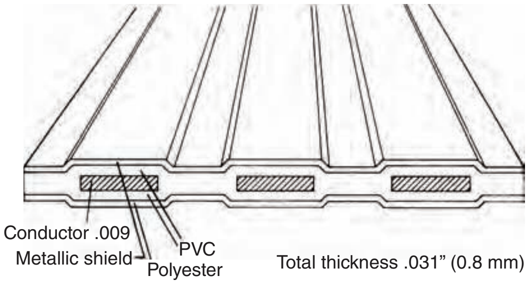


Fig. 28.37 *Schematic section through one design of* NEC *type FCC under-carpet cable. The copper conductors illustrated are the equivalent of No. 12 AWG. The PVC acts as insulation, and the polyester as both insulation and physical protection. All designs require a metallic top shield and a metallic or nonmetallic bottom shield for physical protection.*

Fig. 28.38 *Preterminated 25-pair under-carpet telephone cable. These cables are commercially available in lengths from 5 to 50 ft (1.5 to 15 m) in 5-ft (1.5-m) increments. (Reprinted with permission of AMP.)*

consists of a factory-assembled flat cable (*NEC* type FCC), approved for floor installation *only* under carpet squares, plus the accessories necessary for connection to 120-V power outlets. The cable itself consists of three or more flat copper conductors, placed edge to edge and enclosed in an insulating material (Fig. 28.37). The entire assembly is covered with a grounded metal shield, which, like a metal conduit, provides both physical protection and a continuous electrical ground path. In addition, a bottom shield is required, which is usually heavy PVC or metal.

The cable, when properly installed on a hard, flat surface, is approximately 0.03 in. (0.8 mm) high, and thus essentially undetectable when covered with carpet. Because carpet squares are designed to be readily removable, the entire system can be repositioned to meet changing furniture layout requirements with a minimum of disruption and no structural work. The cable is designed to carry normal physical loads such as office traffic and furniture placement without affecting its electrical performance.

The attractiveness and simplicity of the system led to the development of similarly designed flat, low-tension (voltage) cables for signal and communication wiring (Fig. 28.38) and, more recently, both electrical and fiber-optic cables and accessories for data transmission. Manufacturers also offer a complete line of junction fittings, connectors, adapters, and receptacles (Fig. 28.39).

The problems inherent in this type of on-the-floor wiring system, such as cable crossings, splicing, interfacing with round cable systems, interconnections at floor boxes and fittings, and feed connections from cabinets, underfloor ducts, floor cells, and through-the-floor fittings, have all been solved by a full line of manufactured devices designed for specific situations.

Because under-carpet wiring systems are separate and distinct from wire and conduit systems, they, like underfloor duct systems, are usually shown on a separate electrical plan. A small plan typical of this type is shown in Fig. 28.40. Figures 28.41 and 28.42 are photographs of essential portions of such

Fig. 28.39 *Typical components of an under-carpet wiring system. The under-carpet FCC power cable is shown without the metallic top shield required in actual installation. It is a color-coded, five-conductor cable (neutral, equipment ground, and three circuit conductors or two circuit conductors and an isolated ground conductor). The floor outlets shown are front, single-power outlet; rear (left to right), duplex power outlet (one of which has isolated ground); standard duplex power outlet; and combination data cable, communications, and telephone outlet. (Courtesy of Hubbell, Inc.)*

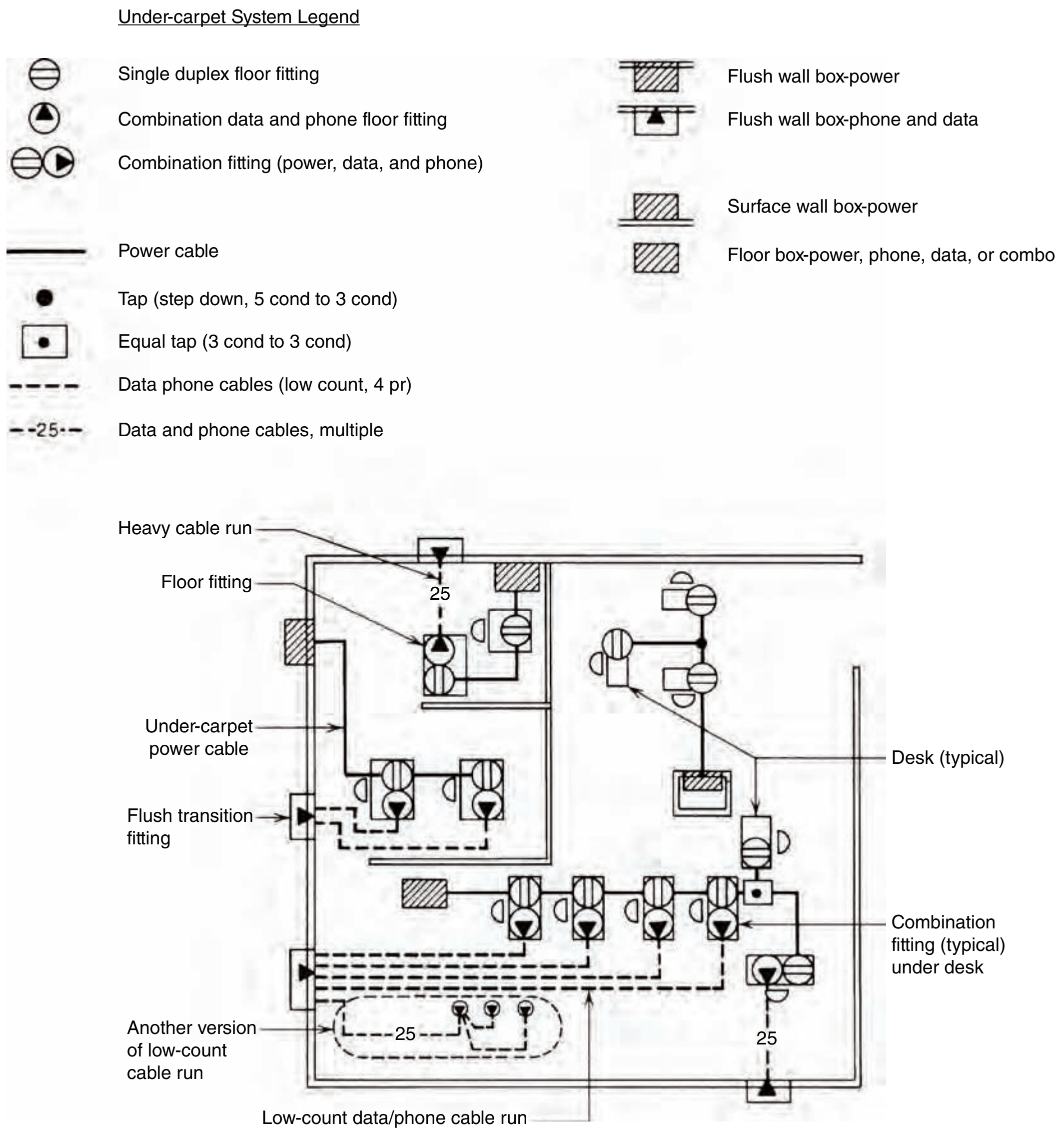


Fig. 28.40 *Typical layout of under-carpet power and low-voltage/data cabling for a small office. A power, phone, and data cable connection on the floor is provided under or immediately adjacent to each desk (see Figs. 28.38, 28.39, 28.41, and 28.42 for typical details). (Reproduced with permission of AMP.)*

an installation. Note that a complex system such as that shown in Fig. 28.42 requires recessing a floor box into the slab, which to an extent contradicts the essential simplicity and flexibility of an under-carpet system. Although these systems, at least in their simplest form, are particularly applicable to retrofit work, their low cost, combined with the inherent advantages of a flexible *floor-level* wiring system—particularly in open office areas—has made them a widely used first choice in new construction as well.

28.30 CEILING RACEWAYS AND MANUFACTURED WIRING SYSTEMS

The need for flexibility in a facility's electrical system coupled with the high cost of underfloor electrical raceway systems encouraged the development of equivalent over-the-ceiling systems. These systems are actually more flexible than their underfloor counterparts because they energize lighting, provide

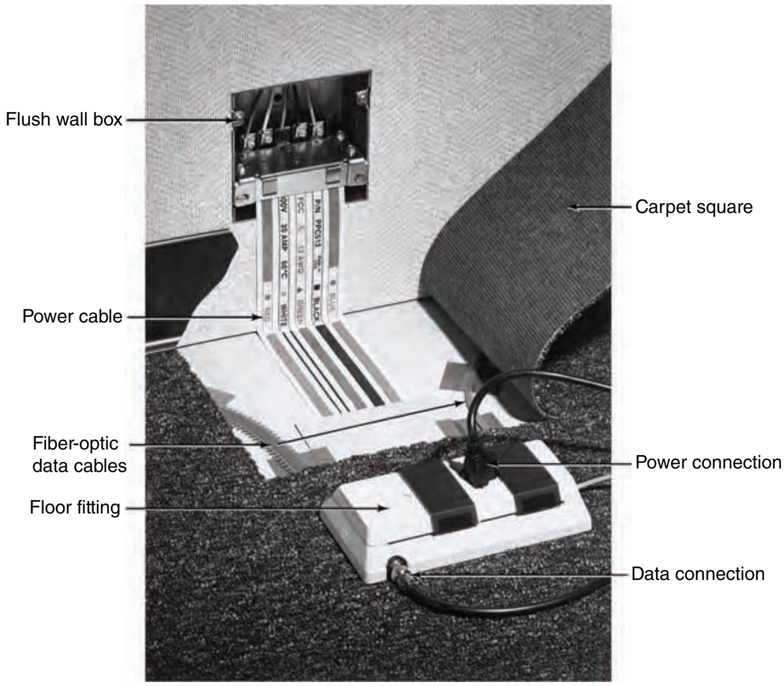


Fig. 28.41 *Under-carpet flat power cables connect to round supply cables in a flush wall box and then extend to a combination power/low-voltage/data floor fitting. Data cables are connected to the combination floor fitting from their system boxes, either individually or via other floor fittings. (Photo courtesy of Walker Systems, A Division of The Wiremold Company.)*

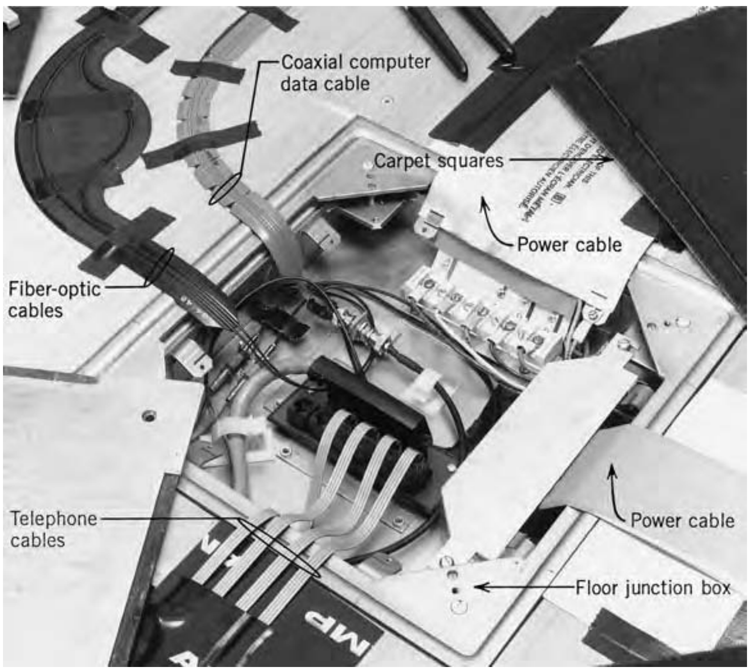


Fig. 28.42 *Four service floor-junction boxes handle under-carpet power, telephone, low-voltage electric, and FO cables. The floor box measures approximately 14 in. (356 mm) square and 2 in. (50 mm) deep. It can accommodate up to four 3-phase power circuits, eight 25-pair telephone/data cables, 24 coaxial cables, or, as illustrated, a mixture of cable types. (Reprinted with permission of AMP.)*

power and telephone facilities, and even supply outlets for the floor above, in addition to permitting very rapid layout changes at low cost. This last characteristic is particularly desirable in stores where frequent display changes necessitate corresponding electrical facility changes. Beyond the extreme flexibility made possible by the ceiling raceway system, it has the additional advantage that the system itself, not being cast in concrete like its underfloor counterpart, can be altered at will. Thus, not only layout changes (as mentioned previously) but also changes in space function can readily be accommodated. This is a particularly important characteristic in merchandising and educational facilities, where space function can be repeatedly changed during the course of a building's life.

Details vary among manufacturers but the systems are essentially the same and, in principle, resemble underfloor systems. A typical system is constructed of metallic or nonmetallic surface-type raceways arranged in a tree formation (i.e., large trunk [header] raceways feed multiple smaller branch [distribution] raceways, and so on). The raceways are hung in the ceiling plenum from the concrete slab above. The hung ceiling must consist of lift-out panels because this type of wiring system is not permitted in spaces rendered inaccessible by the building structure. Header ducts (large area raceways) are fed from electrical panels and from signal, data, and telephone cabinets in the electrical and low-voltage wiring service closets, respectively. Data headers are normally larger than the power header and can carry other low-voltage, low-power signal wiring as well. Distribution ducts (laterals) tap onto the headers. These laterals act as subdistribution raceways, feeding lighting fixtures and data, signal, telephone, and power outlets on the same floor and, via poke-through fittings, outlets on the floor above.

The standard method for extending wiring from ceiling plenum raceways to floor-level or desk-level signal and power outlets uses vertical multi-section raceways fed from the top (see Fig. 28.43). These service poles are available in a large variety of designs, finishes, and cross-sectional raceway areas and are easily installed in almost any location. They may be prewired and usually contain several power outlets, a telephone connection, and possibly data cable outlets. The result in a hung-ceiling office area or an exposed ceiling slab area (Fig. 28.44) is certainly less elegant than that of a floor-level wiring system, but for most users it is satisfactory, and its

Fig. 28.43 *Typical floor-to-ceiling electrical/communication raceway poles. Units are available in a wide variety of shapes, sizes, and cross-sectional configurations in aluminum and steel. (Courtesy of Hubbell Premise Wiring.)*

low cost compared to any type of floor-duct system is a prime redeeming feature.

When electrical connections to poles, lighting fixtures, receptacles, and communication/data outlets are made with hard wiring, considerable field labor is required, with a corresponding high cost. Furthermore, the relative permanence of such wiring lessens the inherent flexibility of the raceway system. To solve both problems, a number of manufacturers have developed a line of modular branch-circuit wiring elements. These, covered in *NEC* Article 604 under the very logical name *manufactured wiring systems*, consist of metal-clad or armored cable sets terminating in polarized plugs. The polarization prevents accidental interconnection of low-voltage, 120- and 277-V systems. Ceiling raceways can be equipped with matching receptacles, and connection to fixtures, poles, and other devices becomes a simple matter of plug insertion (Figs. 28.43, 28.45, and 28.46).

The result is a wiring system of extreme flexibility in which even extensive changes can be made very rapidly with minimal disruption and virtually no mess. Manufactured wiring systems are only permitted in accessible areas, for logical reasons.

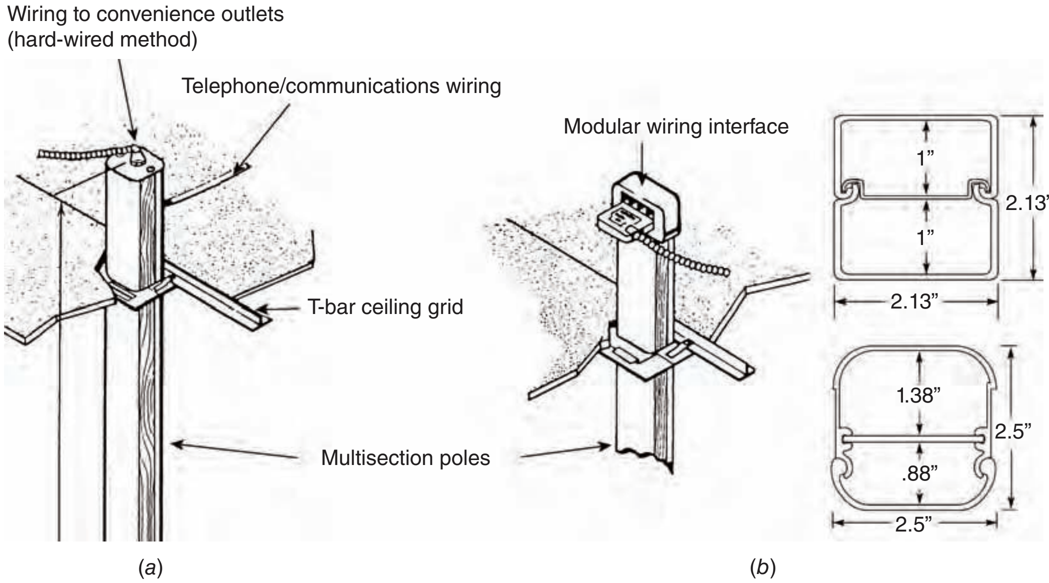


Fig. 28.44 *(a) Poles are fed at the top from the suspended ceiling or from exposed ceiling raceways. These feeds can be either conventional hard-wired or modular (plug-in), as shown. Modular connectors are used for power and low-voltage (telephone, communication, data) wiring. (b) Two of the many cross-sectional configurations available are illustrated. Other designs divide the pole into three sections to suit the specific application. (Courtesy of Hubbell Premise Wiring.)*

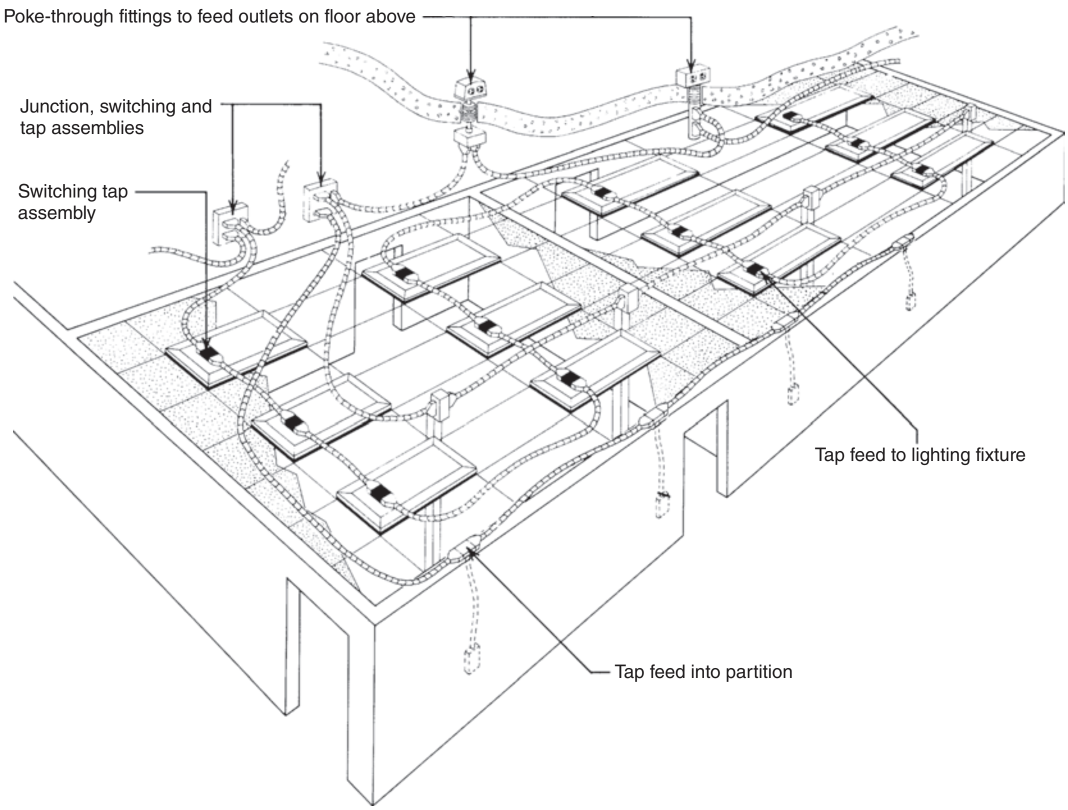


Fig. 28.45 *Manufactured modular wiring assemblies are used for tap connections to feed ceiling lighting fixtures or any other ceiling connection, as well as a complete range of junction, switching, tap, and poke-through units. (Photo courtesy of Walker Systems, A Division of The Wiremold Company.)*

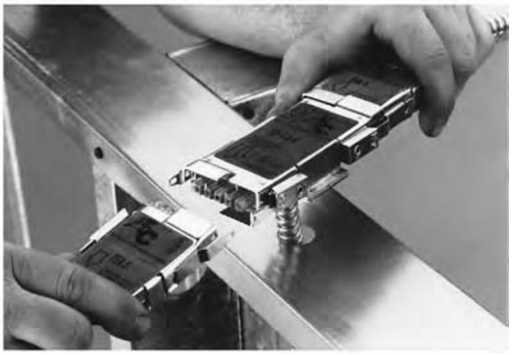


Fig. 28.46 Manufactured modular wiring connectors simplify installation and reduce labor costs initially and during any subsequent rearrangements. (Courtesy of AFC Cable Systems.)

They are also applicable to access floor spaces, as seen in Figs. 28.33 to 28.36 The additional cost of manufactured wiring elements is frequently offset by the labor savings, even upon initial installation and certainly after one or two field changes. Cable sets are available for power (120 V and 277 V), telephone, and all types of low-voltage signal equipment. The cables must be approved for use in conditioned-air plenums and suspended ceilings.

To take full advantage of the potential labor-cost savings inherent in the system, field labor must be minimized. This is accomplished by factory-equipping all utilization equipment, including lighting fixtures, with appropriate plug-in connectors.

CHAPTER 29

Electric Wiring Design

THERE ARE NUMEROUS POSSIBLE solutions to each wiring design problem—some good, some fair, and some poor. Experience guides designers to a solution that best suits the job, within the context of establishing the most cost-effective design, while considering the project design intent and criteria. This chapter opens with a discussion of typical design criteria and continues with wiring design. An electrical design solution intended for construction must meet all the requirements of local and national building codes. In the U.S., building codes generally refer to NFPA 70, the *National Electrical Code* (*NEC*) published by the National Fire Protection Association, as the minimum standard for all electrical design; thus, its requirements are made legally binding on the design team. The electrical design data and procedures presented in this chapter, and in other sections of this book, are based upon *NEC* requirements and are, to the extent possible, current. However, they are intended only as informative materials. Code requirements can change fairly rapidly; the *NEC*, for example, is revised every three years. The designer is strongly advised to obtain and study the latest edition of all codes having jurisdiction, including the *NEC*, to ensure that a proposed electrical design meets the requirements of the current and applicable codes.

29.1 GENERAL CONSIDERATIONS

(a) Flexibility

Every wiring system should incorporate sufficient flexibility in branch circuitry, feeders, and panels to accommodate all reasonably probable patterns, arrangements, and locations of electric loads. The degree of flexibility to be incorporated depends largely upon the type of facility. Thus, laboratories, research facilities, and small educational buildings typically require far more flexibility than do residential, office, and fixed-purpose industrial installations. Part of designing for flexibility includes providing for building and electric service expansion, as experience has demonstrated that most facilities will grow, both physically and in electrical demand. Overdesign, however, is as bad as underdesign, being wasteful of money and resources, both initially and in operation. A clear understanding of the client's needs, as defined in an Owner's Project Requirements document, can greatly assist in reaching a reasonable compromise between current and future needs.

(b) Reliability

The reliability of electrical power within a facility is determined by two factors: the incoming utility service and the building's electrical system. The service record of the utility should be studied along with the economic impacts of a power outage to determine whether, and to what extent, standby power equipment is justified (see Sections 27.39 and 29.21). Emergency equipment requirements for the safety of building occupants are established by local, state, and national building codes.

Beyond the electrical service point, the reliability of power is entirely dependent upon the wiring and distribution system. Here, too, economic studies must be made to determine the quality of equipment and the extent of redundancy (duplicate equipment) to be installed. The subject of reliability is complex, and only a few general principles are noted here.

1. The reliability of an electric system is only as good as that of its weakest element. Therefore, it may be necessary to provide redundancy at anticipated weak points in the system.
2. The electrical service and the building distribution system act together. An extremely reliable (and expensive) service is of little use if the power cannot reach the desired points of usage.
3. Critical loads within the facility should be defined to determine how best to serve them reliably. This can be done by establishing reliable power paths or by furnishing individual standby power packages for such loads. The latter course is often chosen for health-care facilities and critical loads in other buildings.

(c) Safety

Although rigid adherence to the requirements of the *NEC* and other applicable NFPA codes ensures an initially safe electrical installation, the designer must be alert to the potential for electric hazards caused by misuse or abuse of equipment or by equipment failure. Also, attention to the physical size of equipment during design can eliminate the often-encountered hazards caused by obstruction of access spaces, passages, closets, and surfaces with electric equipment. Finally, lightning protection should also be considered under the heading of safety; this topic is discussed in Chapter 25.

(d) Economic Considerations

This area of concern can readily be divided into two frequently interrelated items: first cost and life-cycle cost. All other factors being equal, first cost depends largely upon whether an owner is interested in the minimum first cost or the minimum overall ownership cost. These two costs frequently stand in inverse relationship to one another (exceptions are mentioned later). Low first-cost equipment generally results in higher energy costs, higher maintenance costs, and shorter life—with a resulting higher life-cycle cost.

The electrical energy cost related to building operations is directly related to energy consumption, with one exception. That exception is the utility company's demand charge (discussed in Sections 26.13 and 26.14). Means for minimizing this cost are covered in detail in Section 26.14. Here, there is a coincidence, whereby a reduction in both first cost and operating costs can be achieved. Load-leveling equipment permits the electrical distribution system to be sized without consideration of coincident load peaks, thus resulting in smaller equipment that operates more efficiently—near its full-load capacity. All other reductions in electric energy cost flow directly from the corresponding reduction in energy consumption.

(e) Energy Considerations

These concerns are complex, involving consideration of energy codes and budgets, energy conservation and energy efficiency techniques, and energy control approaches.

Buildings designed under a number of scenarios may be effectively subject to energy budget limitations (expressed in Btu/ft^2/yr [kWh/m^2 per year]). Although the lion's share of this budget is taken by heating/cooling and lighting systems, the electrical distribution system is also subject to limits in some codes/standards. Most important among these is ASHRAE Standard 90.1. Detailed energy conservation considerations are discussed in Section 29.5.

(f) Space Allocations

The general impression that electrical equipment is small and easily concealed is accurate only for wire and conduit. Panels, motor control centers, busduct, distribution centers, switchboards, transformers, and so on can be large, bulky, noisy, and highly sensitive to tampering and vandalism. Thus, space allocations must be concerned with ease of maintenance, ventilation potential, expandability, centrality (to limit the length of distribution runs), limiting access to authorized personnel, and noise control, in addition to the fundamental consideration of space adequacy.

(g) Special Considerations

These depend upon the nature of the facility and may include items such as security, central and/or remote controls, interconnection with other facilities, and the like.

29.2 LOAD ESTIMATING

When initiating the electrical system design for a facility, it is necessary to estimate the total building load in order to plan for such spaces as transformer rooms, conduit chases, and electrical closets. An estimated load is also required by the local power company well in advance of the start of construction. An exact load tabulation can be made only after the design is completed, but because this is often several months later, a good preliminary estimate is required. Such an estimate can be made from the figures given in Table 29.1. These values represent averages. When it appears that a building will have heavier or lighter loads because of lighting levels, a design (such as a green building) that exceeds energy codes, load-management equipment, the aggressive use of passive systems, or other factors, the values should be modified accordingly. The figures given in the individual categories should be added without application of demand or diversity factors in order to obtain the maximum load for which the building service equipment must be sized—in the absence of electric load-control (load-leveling) equipment. (Noncoincident loads, such as heating and cooling in the same space, are not combined.)

At this point in the design process, an analysis can be made to determine the feasibility of incorporating electric load-control equipment into the facility. Inputs to such a study include the utility's complete rate schedule, including all penalty clauses, a detailed analysis of the building's equipment load patterns, and any external constraints such as maximum loads imposed by power and energy budgets. Equipment load patterns must be carefully analyzed because they determine load sheddability. Thus, for kitchen equipment, load interruption may be unacceptable, but shifting of cooking time by half an hour may be quite feasible. For HVAC equipment, building thermal inertia and pushing maximum and minimum temperature and humidity limits may permit considerable latitude without adverse effects. As explained in Section 26.14, the degree and duration of load shedding are a function of the type of control equipment utilized. To repeat what was previously stated—load control affects maximum demand, with only minor effect on total energy consumption. The external constraints referred to are the energy budgets recommended or required by codes, legislation, and funding bodies.

After a load-control analysis is complete, or simultaneously with such an analysis, a building energy consumption analysis must be performed. This may be done manually, but numerous computer programs are readily available that not only increase accuracy but also permit consideration of more factors. The results of this analysis will indicate whether the target electrical energy budget is being met. If not, loads must be modified by reconsideration of proposed systems (and perhaps system design criteria), by incorporating energy conservation devices and techniques into the electrical system design, and by preparing energy-use guidelines that will be applied when the building is occupied. Because this last item depends for success upon the day-to-day voluntary actions of the building's operators and occupants, experience has shown that it should not be considered as a major conservation factor. Ongoing building commissioning can be a powerful assist in changing this situation. Conservation measures are covered in Section 29.5.

The electrical loads in any facility can be categorized as follows:

1. Lighting
2. Miscellaneous power, which includes data-processing equipment, convenience outlets, and small motors
3. Heating, ventilating, and air-conditioning (HVAC) equipment
4. Plumbing and other piping-based systems
5. Mechanized transportation equipment and fixed material-handling equipment
6. Kitchen equipment
7. Special equipment

Category 1 is covered by column II of Table 29.1. Note, however, that lighting loads are carefully prescribed in ASHRAE Standard 90.1 and that these prescribed loads should be used where this standard has jurisdiction (which is most of the U.S.). Contradictions between requirements in applicable codes/standards must be adjudicated by local authorities

TABLE 29.1 Electric Load Estimating[a]

I	II	III	IV	V	VI
	Volt-Amperes per ft^2 (per m^2)[b]				Ten-Year Percent Load Growth
			Air Conditioning[f]		
Type of Occupancy	Lighting[c, d]	Misc. Power[e]	Electric	Nonelectric	
Auditorium					
General	1.0–2.0 (10.8–21.5)	0	12–20 (129–215)	5–8 (54–86)	20–40
Stage	20–40 (215–430)	0.5 (5.4)			
Art gallery	2.0–4.0 (21.5–43.1)	0.5 (5.4)	5–7 (54–75)	2.0–3.2 (21.5–34.5)	20–40
Bank	1.5–2.5 (16.2–26.9)		5–7 (54–75)	2.0–3.2 (21.5–34.5)	30–50
Cafeteria	1.0–1.6 (10.8–17.2)	0.5 (5.4)	6–10 (65–108)	2.5–4.5 (26.9–48.4)	20–40
Church and synagogue	1.0–3.0 (10.8–32.3)	0.5 (5.4)	5–7 (54–75)	2.0–3.2 (21.5–34.5)	10–30
Computer area	1.2–2.1 (12.9–22.6)	2.5 (26.9)[g]	12–20 (129–215)	5–8 (54–86)	50–200
Department store					
Basement	3–5 (32.3–53.8)	1.5 (16.2)			
Main floor	2.0–3.5 (21.5–37.7)	1.5 (16.2)	5–7 (54–75)	2.0–3.2 (21.5–34.5)	50–100
Upper floor	2.0–3.5 (21.5–37.7)	1.0 (10.8)			
Dwelling (not hotel)			—	—	
0–3000 ft^2 (0–280 m^2)	3.0 (32.3)	5.0 (53.8)	—	—	50–100
3000–120,000 (280–11,150)	0.4 (4.3)	0.15 (1.6)	—	—	—
above 120,000 (>11,150)	1.5–2.5 (16.2–26.9)	2.0 (21.5)	—	—	—
Garage (commercial)					10–30
Hospital	1.0–3.5 (10.8–37.7)	1.5 (16.2)	5–7 (54–75)	2.0–3.2 (21.5–34.5)	40–80
Hotel	1.0–2.0 (10.8–21.5)	0.5 (5.4)			
Lobby	1.0–1.5 (10.8–16.2)	1.0 (10.8)	5–8 (54–86)	2.0–3.5 (21.5–37.7)	
Rooms (no cooking)	2.0–3.0 (21.5–32.3)	5–20 (54–215)	3–5 (32–54)	1.5–2.5 (16.2–26.9)	30–60
Industrial loft building	1.2–2.2 (12.9–23.7)	0.5 (5.4)	—	—	50–100
Laboratories	1.5–3.0 (16.2–32.3)	1.5 (16.2)	6–10 (65–108)	2.5–4.5 (26.9–48.4)	100–300
Library	1.0–2.0 (10.8–21.5)	0.5 (5.4)	5–7 (54–75)	2.2–3.2 (23.7–34.5)	30–40
Medical center	1.5–3.5 (16.2–37.7)	2.5 (26.9)	4–7 (43–75)	1.5–3.2 (16.2–34.5)	50–80
Motel	1.2–2.5 (12.9–26.9)	0.5 (5.4)	—	—	30–60
Office building	1.5–2.8 (16.2–30.1)	2.5 (26.9)	4–7 (43–75)	1.5–3.2 (16.2–34.5)	50–80
Restaurant			6–10 (65–108)	2.5–4.5 (26.9–48.4)	20–40
School	2.0–2.5 (21.5–26.9)	2.0 (21.5)	3.5–5.0 (38–54)	1.5–2.2 (16.2–23.7)	50–80
Shops	2.0–3.5 (21.5–37.7)	0.5 (5.4)			
Barber and beauty	2.0–3.0 (21.5–32.3)	0.5 (5.4)			
Dress	2.0–3.0 (21.5–32.3)	0.5 (5.4)	5–9 (54–97)	2–4 (22–43)	
Drug	2.0–3.5 (21.5–37.7)	0.25 (2.7)			40–80
Miscellaneous goods	0.25–1.0 (2.7–10.8)	—	4–7 (43–75)	1.5 to 3.2 (16.2–34.5)	
Hat, shoe, specialty	0.3 (3.2)	—			
Warehouse (storage)	0.25 (2.7)	—	—	—	10–30
In the buildings listed except single dwellings:					
Halls, closets, corridors,	0.5 (5.4)	—	—	—	
storage spaces	0.25 (2.7)	—	—	—	

[a]Figures assume energy-conservation techniques applied.

[b]These figures do not include allowance for future loads.

[c]The figures given in Article 220 of the *NEC* are minimum figures for calculation of electric feeder sizes.

[d]See Section 15.5 for a discussion of power limits.

[e]These figures are based on experience and must be applied judiciously.

[f]Includes the loads of air-handling equipment and pumps.

[g]This figure does not include the power used by the computer (which can vary widely depending upon the type being used).

before a design is established. Consult the current version of ASHRAE Standard 90.1 for details of prescribed lighting loads.

Category 2, column III, includes, in addition to receptacles and small motors, such items as desktop computers and data-processing terminals, including all peripheral equipment, plus plug-in heaters, water fountains, and so on.

Category 3, column IV, includes all loads imposed by the HVAC equipment. This includes fuel pumps, boiler motors, air-handling units, exhaust fans, and so forth. Also included in column IV, for air-conditioning loads, are refrigeration compressors. This item is omitted in column V because such air conditioning utilizes absorption machines that do not use electricity for primary power. When cooling is not anticipated, the HVAC load is still appreciable because of heating and ventilating requirements. A rough estimate for the load in this situation would be two-thirds of the loads in column V.

Category 4 includes all loads associated with water and sanitary systems, including house water pumps, air compressors and vacuum pumps, sump pumps and ejectors, well pumps and fire pumps, water heaters, and pneumatic tubes, plus special items such as display fountain pumps. Also included in this category are electric loads associated with fixed piping-based systems such as cooking gas, medical gas piping, distilled water systems, and so on.

Because these loads vary widely with local conditions and with specific facility design as much as with the type of facility, an estimate cannot be made on a volt-amperes per unit area basis by type of building. Thus, no value is included in Table 29.1. If actual data cannot be used, it is helpful to remember that plumbing/piping electrical loads are relatively small, rarely exceeding 20% of the HVAC system electric load (although, for the most part, they are unrelated to the HVAC components).

Category 5, vertical transportation, is related to floor area in some types of buildings but not in others. A close estimate of power and energy requirements can be made by the project's elevator consultant. Lacking this, a fair estimate can be made from the data given in Chapters 32–34. In addition to elevators, escalators, moving walkways, and ramps, these loads should include dumbwaiters, horizontal and vertical conveyors, trash and linen transport systems, automated container delivery, and fixed conveyors. These loads are readily available from a material transport consultant, who is frequently also the elevator consultant.

Category 6, kitchen equipment, is also not included in Table 29.1, although obviously present in all restaurants, most hospitals, and some office and religious-use buildings. The reason for this omission is that the primary power for the major load, cooking equipment, may be either gas or electric. Other large-energy-use equipment such as dishwashers can be electric, gas, or steam-fed. Furthermore, no correlation can be made between the facility type, floor area, and load, even if electrically powered, because population and schedule are also major factors. When kitchens are planned, a kitchen consultant or other experienced planner can supply an estimate of the electric power requirements.

Category 7, special equipment, is so varied that no values can be listed. This category includes such items as laboratory equipment, shop loads, display area loads, floodlighting, canopy heaters, display window lighting, industrial loads, and so on. Data for these loads must be gathered for individual items of equipment and added to the foregoing totals.

Table 29.2 gives a tabulation of service entrance size in amperes, based on single- and 3-phase service for typical occupancies. These figures are intended for rough estimating purposes and should be adjusted after the design is completed.

TABLE 29.2 Nominal Service Size in Amperes

Nominal service sizes are 100 A, 150 A, 200 A, 400 A, 600 A

	Area in ft^2 (m^2)				
Facility	**1000 (93)**	**2000 (186)**	**5000 (465)**	**10,000 (929)**	**Remarks**
Single-phase, 120/240 V, 3-wire					
Residence	100 A	100 A	150 A	—	Minimum 100 A
Store[a]	100 A	150 A	—	—	
School	100 A	100 A	150 A	—	
Church[a]	100 A	150 A	—	—	
3-phase, 120/208 V, 4-wire					
Apartment House	—	—	100 A	150 A	
Hospital[a]	—	—	200 A	400 A	
Office[a]	—	100 A	400 A	600 A	
Store[a]	—	100 A	400 A	600 A	
School	—	100 A	100 A	200 A	

[a]Fully air-conditioned using electric-driven compressors. Based upon figures in Table 29.1.

29.3 SYSTEM VOLTAGE

Several voltage systems (arrangements) are commonly available in the United States and Canada. (See *NEC* Article 230, "Services," for code requirements.)

(a) 120-V, Single-Phase, 2-Wire

This arrangement (Fig. 29.1) is used for the smallest facilities, such as outbuildings, and isolated small loads of up to 6 kVA. The load is calculated by multiplying current and voltage. For 60-A service, which is the normal limit for this type of service, no more than 50 A are usually drawn. Thus

$$VA = 120 \times 50 = 6000 \text{ VA} = 6 \text{ kVA}$$

The nominal system voltage is 120 V, although it is also referred to as 110 V and 115 V.

(b) 120/240-V, Single-Phase, 3-Wire

This system (Fig. 29.2) is for somewhat heavier loads. The code requires that all one-family residences with six or more 2-wire circuits or a net computed load (by code calculation) of 10 kVA or more have a minimum of 100-A, 3-wire service. Service disconnect for 100-A service would be a 100-A, 2-pole, solid neutral switch, fused at no more than 80% of the rating, or 80 A. This is usually written 100A, 2P & SN, 80AF. This service is used principally for residences, small stores, and other occupancies where the load does not exceed 80 A or 19.2 kVA. The load is calculated thus:

$$\text{kVA} = \frac{\text{V} \times \text{I}}{1000} = \frac{240 \times 80}{1000} = 19.2$$

Although it may appear otherwise, the neutral carries no more than full-load current. Note that each "hot leg" of the 3-wire system carries line current. Thus, total load can also be calculated:

$$\text{load kVA} = \text{twice load on each line}$$

Assuming a balanced 80-A load:

$$\begin{aligned}\text{total kVA} &= 2 \times 80 \text{ A} \times 120 \text{ V}\\ &= 2 \times 9600 \text{ VA} = 19{,}200 \text{ VA}\\ &= 19.2 \text{ kVA}\end{aligned}$$

If the loads were unbalanced with, say, 30 A in one line and 50 A in the other, the total load would be

$$\begin{aligned}120 \times 30 + 120 \times 50 &= 3600 + 6000 = 9600 \text{ VA}\\ &= 9.6 \text{ kVA}\end{aligned}$$

Actual system voltages can be 120/240, 115/230, or 110/220, although 120/240 is the accepted industry standard. Normal receptacle and lighting loads at 120 V are connected between line and neutral. Heavier loads, such as for a clothes dryer or an electric stove, are connected between phase lines at 240 V.

For example, to find the line currents caused by the three loads shown in Fig. 29.3:

1. 120-V, 1200-W iron, line A to neutral
2. 120-V, 1440-W hair dryer, line B to neutral
3. 240-V, 4800-W clothes dryer, line A to line B

calculate

$$I_1 = \frac{1200}{120} = 10 \text{ A}$$

$$I_2 = \frac{1440}{120} = 12 \text{ A}$$

$$I_3 = \frac{4800}{240} = 20 \text{ A}$$

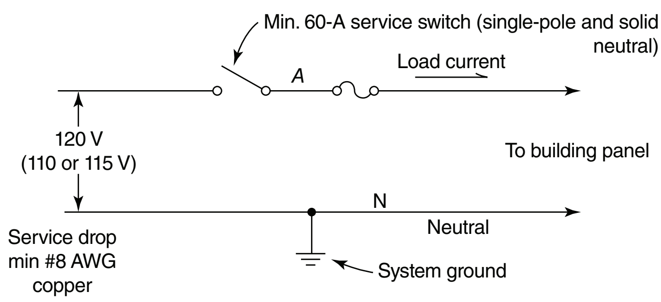


Fig. 29.1 *Shown is a 120-V, single-phase, 2-wire service. This is also the arrangement of a typical branch circuit.*

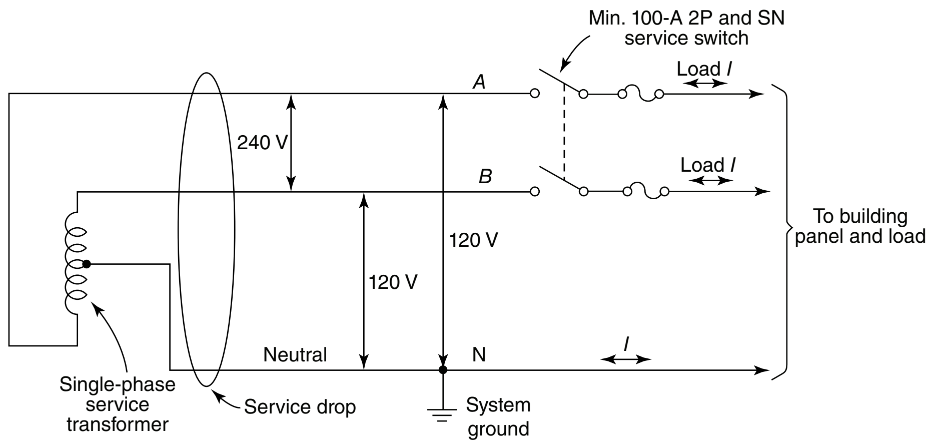


Fig. 29.2 *Shown is a 120/240-V, single-phase, 3-wire service. The single-phase transformer, which is normally located on the power company's pole along a street or road, is center-tapped to establish a neutral. The neutral connection is always grounded.*

Note that the neutral only carries the unbalance of 2 A (see Fig. 29.3).

$$\text{Total current in line A} = 20 + 10 = 30 \text{ A}$$

$$\text{Total current in line B} = 20 + 12 = 32 \text{ A}$$

$$\text{Total current in neutral N} = 2 \text{ A}$$

$$\text{Total load} = 120(30) + 120(32) = 3600 + 3480 = 7440 \text{ VA}$$

or

$$\text{Loads are } 1200 + 1440 + 4800 = 7440 \text{ VA}$$

Because the loads are almost entirely resistive heating loads (small hair dryer motor and approximately a 1/6-hp [0.12 kW] dryer motor), the entire load has a power factor of almost 1.0. This, however, affects only energy calculations because equipment is sized, in general, by kVA capacity. The 120/240-V, single-phase system is derived from a center-tapped, single-phase transformer.

(c) 120/208-V, Single-Phase, 3-Wire

Although this system (Fig. 29.4) appears similar to the one described in Section 29.3*b*, it is really part of a 3-phase system. It is most often found *within* a building that takes 3-phase service rather than constituting a service voltage arrangement. It is used to serve a load that does not require 3-phase, 4-wire but does require a voltage higher than 120 V. Calculation of loads and line currents is considerably more complex than in Section 29.3*b* because

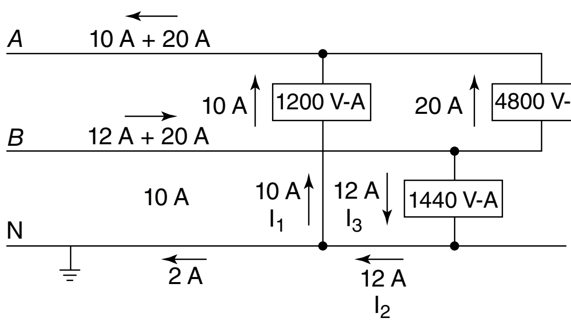


Fig. 29.3 *An example 120/240 V, 3-wire distribution. Note that the neutral carries the difference in current between the A and B legs and therefore a maximum that is equal to the current in one of the legs (when the other is zero).*

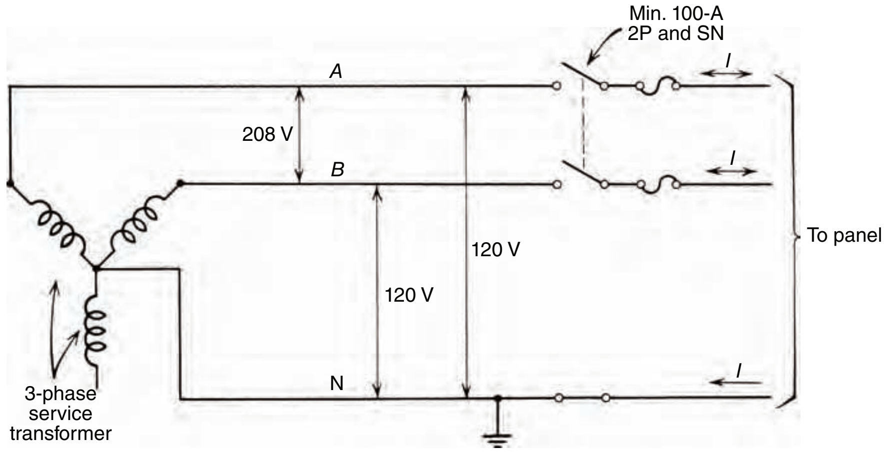


Fig. 29.4 *Shown is a 120/208-V, single-phase, 3-wire service. This arrangement comprises two-thirds of the full 120/208-V, 3-phase, 4-wire connection shown in Fig. 29.5.*

of the 120° phase displacement between phases A and B. Here, as before, the neutral carries no more than line current, regardless of whether the system is balanced.

(d) 120/208-V, 3-Phase, 4-Wire

This system (Fig. 29.5) is a widely used 3-phase arrangement applicable to all facilities except very large ones. In the latter, lengths of feeders and sizes of loads become so great that a higher system voltage is required. In this system, 120-V loads such as lighting, computers and accessories, receptacles, and so on, are fed at 120 V by connection between a phase leg (Fig. 29.6) and neutral. Motors larger than ½ hp (0.37 kW) and all 3-phase loads are fed at 208 V by connection to the 3-phase legs. Single-phase, 208-V loads such as heaters are accommodated as described in Section 29.3*c* by connection between two phase legs. Such loads are often referred to as *2-pole* loads, alluding to the 2-pole current breakers used to feed them.

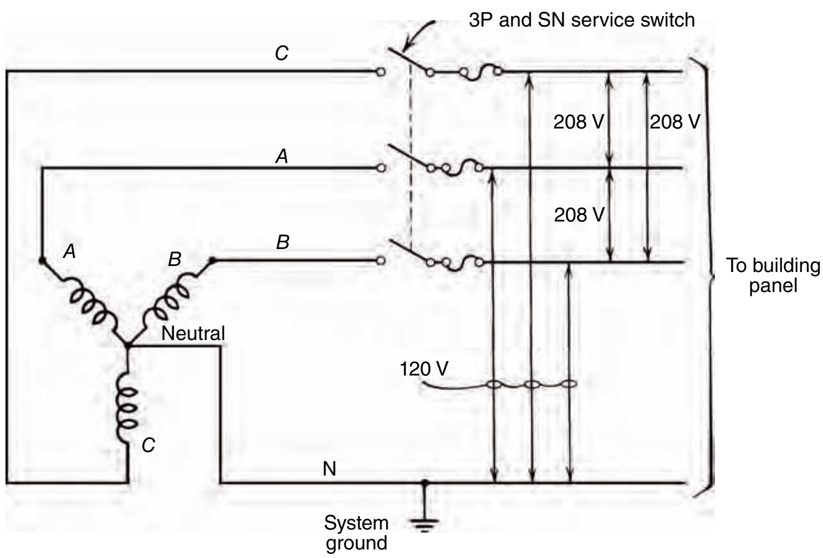


Fig. 29.5 *Shown is a 120/208-V, 3-phase, 4-wire system. The neutral connection is connected to the system ground and is not broken by the service switch.*

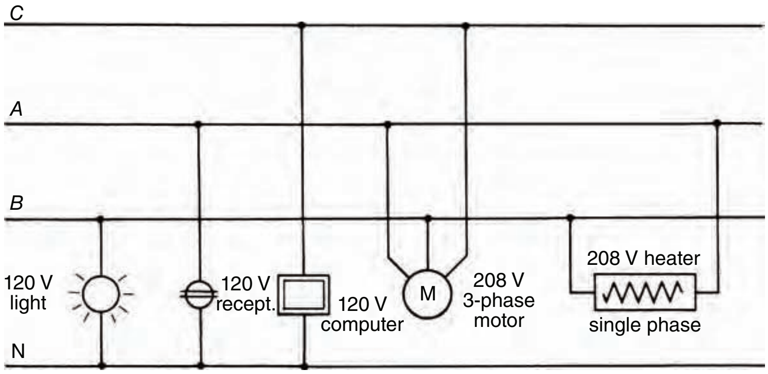


Fig. 29.6 *The flexibility of the 120/208-V system is illustrated; this accounts for its wide usage. Loads are shown schematically. In practice, the loads are fed via protective devices in the panel (omitted here for clarity). A, B, C, and N represent the panel buses.*

(e) 277/480-V, 3-Phase, 4-Wire

This system (Figs. 29.7 and 29.8) is applicable to large buildings (either horizontally or vertically) where lighting is principally fluorescent and/or high-intensity discharge (HID), and the 120-V load does not exceed one-third of the total load. It provides 277 V for fluorescent and HID lighting and 480 V for machinery. Small (3- to 25-kVA) dry-type transformers are used to step down from 480 V for 120-V loads. This system is ideally suited to multistory office buildings and large single-level or multilevel industrial buildings. Cost savings are generated by the smaller feeder and conduit sizes and smaller switchgear, which more than offset the additional cost of step-down transformers for the 120-V loads.

As an example of the economies possible with this system, consider the wiring required for a 15-kW heater. At 3-phase, 208 V:

$$I = \frac{15{,}000\ \text{W}}{\sqrt{3} \times 208\ \text{V}} = 42\ \text{A}$$

requiring No. 8 RHW wire (45-A capacity). At 480 V:

$$I = \frac{15{,}000\ \text{W}}{\sqrt{3} \times 480\ \text{V}} = 18\ \text{A}$$

requiring only No. 12 RHW wire (20-A capacity). This voltage system is also referred to as 265/460 V and 255/440 V.

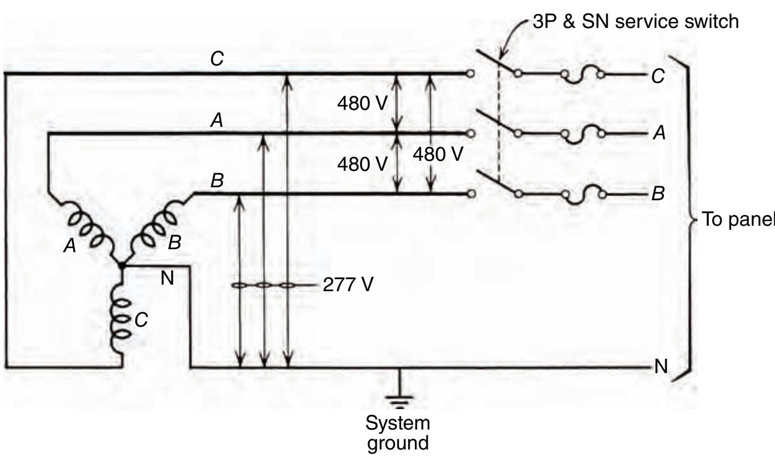


Fig. 29.7 *Shown is a 277/480-V, 3-phase, 4-wire service system. The system is identical to the 120/208-V system shown in Fig. 29.5 except for the voltages.*

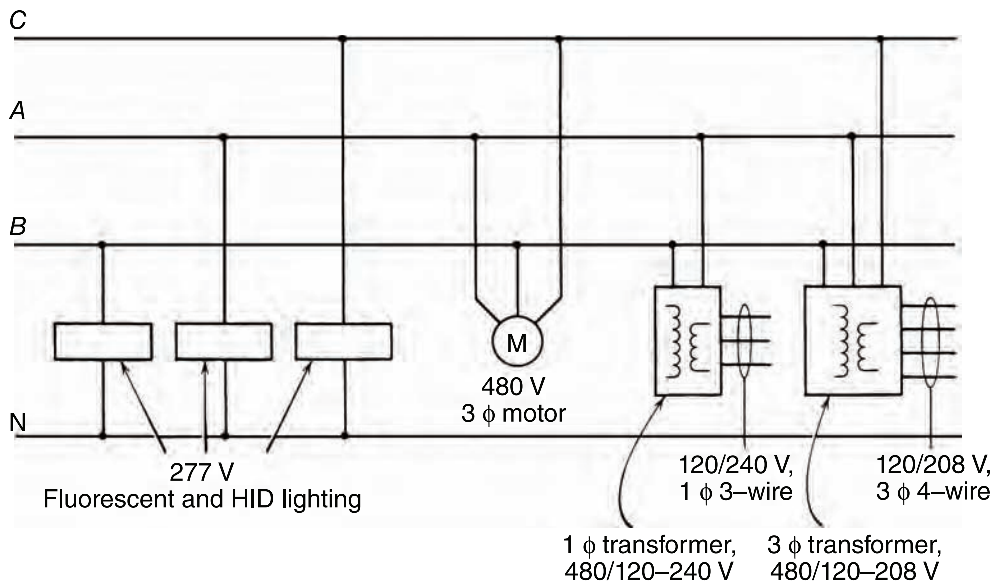


Fig. 29.8 *Normal load arrangement for a 277/480-V system is illustrated. The lighting can be fluorescent or HID. Transformers, either single-phase or 3-phase, supply 120 V for receptacles and 208 V for loads requiring that voltage.*

Voltages above 150 V to ground are generally avoided in residential branch circuits but may be used in commercial and industrial facilities within the guidelines established by the *NEC*.

(f) 2400/4160-V, 3-Phase, 4-Wire

This system is used only in very large commercial or industrial buildings with machinery requiring these voltages. The cost of running these voltages within a building is high because of *NEC* requirements and the inherently higher cost of 5-kV equipment. A detailed cost and engineering analysis by an electrical engineer is required for each case. Voltages above this level are widely used in large industrial plants but are beyond the scope of this book.

Reference was made earlier to the varied "voltages" assigned to the same voltage system. Thus, at the lowest level, there is 110, 115, and 120 V; at the next level, 200, 208, 220, 230, and 240 V; at the next, 255, 265, and 277 V; and finally, 440, 465, and 480 V. These voltage terminology differences arise because of the historic difference between transformer voltage standards, which establish the *system* voltage, and motor voltage standards, which govern *utilization* voltage (Table 29.3). Present motor voltage standards are in agreement with the system voltage standards. Note the close

TABLE 29.3 Standard System and Utilization Voltages[a,b]

System Voltage (Transformers)		Utilization Voltage[c] (Motors)	
Nominal	With 4% Drop[c]	Current Standard[d]	Obsolete Standard
120	115.2	115	110
208[d]	199.7	200	208
240[d]	230.4	230	220
480	460.8	460	440
600	576.0	575	550

[a]To eliminate any confusion between system and utilization voltages, the current NEMA standards are tabulated here.

[b]When specifying transformers, use system voltages; for motors, use utilization voltage.

[c]Note that utilization voltage corresponds to a 4% drop from the system voltage, well within the normal motor tolerance.

[d]Motors for 208-V systems are rated 200 V. Motors for 240-V systems are rated 230 V. They cannot be used interchangeably without seriously affecting motor performance.

TABLE 29.4 Effects of Undervoltage on Utilization Equipment[a]

Load	10% Undervoltage
Lighting	
Incandescent	Output reduced 30%
Fluorescent	Output reduced, poor start
Mercury vapor	Low output, poor start
Motors	20% lower torque, hotter operation, reduced life, overloading
Heaters	20% reduction in output
Small tools	Stalling, low power

[a]Computers and peripherals are generally supplied with voltage-regulating power supplies that make them tolerant of +/–10% variation in steady-state supply voltage. Conversely, they are highly intolerant of rapid supply voltage fluctuation.

correspondence between motor standard voltage and system voltage with a (normal) 4% feeder voltage drop. Thus, on 240- and 480-V systems respectively, 230- and 460-V motors are suitable.

Difficulties arise in the application of 230- and 240-V motors to a 208-V system. Although motors will operate at plus or minus 10% voltage, 230- and 240-V motors should *not* be used on 208-V systems. Instead, motors specially wound for 200 V should be specified. A brief summary of the effects of undervoltage is given in Table 29.4.

29.4 GROUNDING AND GROUND-FAULT PROTECTION

The vast majority of secondary wiring systems are solidly grounded. The reasons for this arrangement are several and varied. Among them are:

1. To prevent sustained contact between a low-voltage secondary system and a high-voltage primary system in the event of an insulation failure. Such contact could cause a breakdown of the secondary system insulation and severely endanger system users.
2. To prevent single grounds from going unnoticed until a second ground occurs, which would extensively disable the secondary system.
3. To permit locating ground faults with ease.
4. To protect against voltage surges.
5. To establish a neutral at zero potential for safety and for reference.

Points 2 and 4 are highly technical, and a full explanation is beyond the scope of this book. Point 5 requires that the neutral in a single secondary system is:

1. Never interrupted by switches or other devices
2. Connected to ground only at one point—the service entrance
3. Color-coded (in the United States) white, natural gray, or by three continuous white stripes on any insulation color other than green, along the entire conductor length, for easy recognition

A typical service-grounding diagram is given in Fig. 29.9. Universal acceptance and use of grounded secondary 120-V systems *introduces* another shock hazard while eliminating the dangers described previously. This is shown in Fig. 29.10*a*. An accidental fault within an appliance could connect the metal case of the appliance to the line. This can occur with such common devices as an electric saw, a clothes washer or dryer, or a food mixer. A person contacting the appliance housing and simultaneously a ground, such as a water pipe, would receive a nasty 120-V shock. If the contact were made with wet hands, the shock could be fatal. Unfortunately, however, until such an incident occurred, the internal fault would remain an unnoticed source of danger.

To eliminate this hazard, appliance manufacturers have always recommended that appliance housings be grounded to a cold-water pipe. In addition, the appliances are supplied with 3-wire plugs: two wires connected to the appliance and the third wire to the housing. To accommodate such plugs and to provide a ground path, the *NEC* requires all receptacles to be of the grounding type and all wiring systems to provide a ground path, separate and distinct from the neutral conductor (see Fig. 27.40). The result of such wiring is shown in Fig. 29.10*b*, where the ground current passes harmlessly through the internal fault, along the ground-wire path, and back to the panel. A person contacting

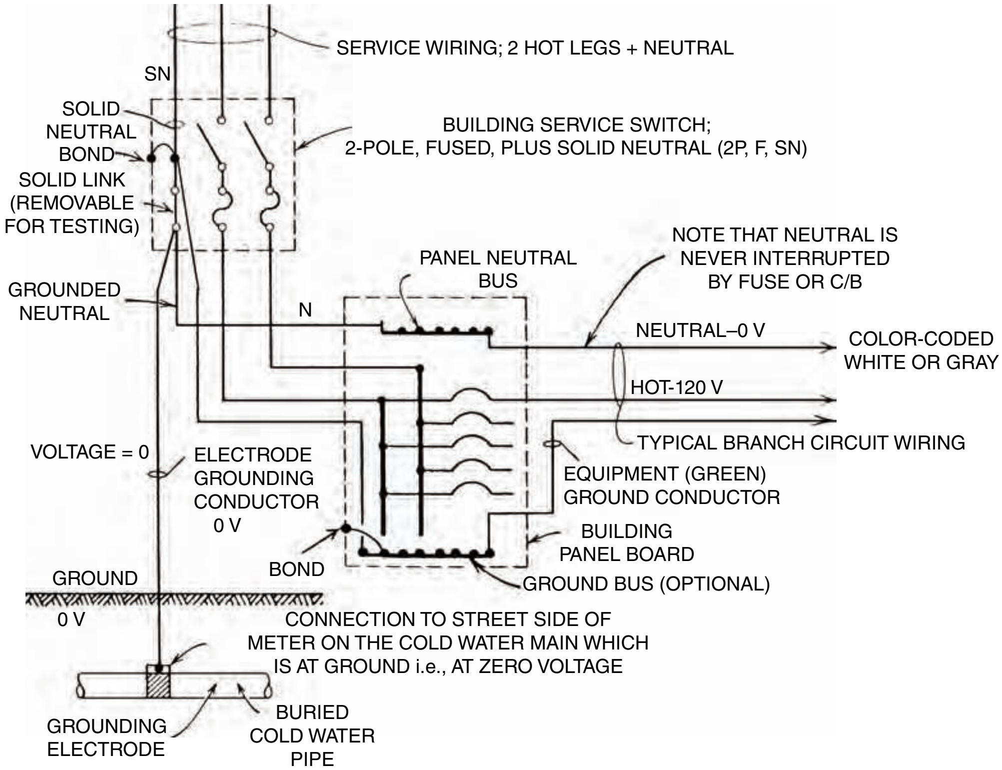


Fig. 29.9 *Typical service-grounding arrangement. Note that the grounded neutral is unbroken throughout. The ground bus, if present, is separate and distinct from the neutral bus, and both are grounded at the service entrance point. For the sake of clarity, not all bonding connections, which are required to ground all non-current-carrying metal parts of the electrical system (boxes, enclosures, conduits, etc.), are shown.*

the appliance housing establishes a parallel ground path. However, because this path is usually of much higher resistance than the ground-conductor path, only a very small current will flow. Wet hands materially reduce contact resistance, and shock current can increase to a dangerous level. If the ground current is sufficiently high, the branch circuit breaker or fuse opens, disconnecting the circuit.

When wiring systems are installed in metallic conduit, the conduit itself or the conduit plus a separate conductor within the conduit may be used as the grounding path. The latter method, with the additional ground wire, is far preferable, as explained in Fig. 29.10. When nonmetallic or flexible metallic wiring (Romex or BX) is used, a separate grounding conductor run with the regular circuit conductors *must* be used.

All insulated ground conductors must have their covering colored green for identification as a grounding conductor. Many industrial installations install complete “green-ground” systems in an attempt to eliminate shock hazard and reduce insulation failures. This has not been entirely successful for the reason noted previously—in order to clear the ground fault, its current must be high enough to trip the branch circuit protective device. Otherwise, the ground fault continues to “leak,” unnoticed by the system’s protective devices. Unfortunately, ground faults are by nature low-current, leak-type faults, because they result from weak spots in insulation, dirt accumulation, and so on. Therefore, although the shock hazard is greatly reduced by the green-ground path, the fault continues to leak and arc until it becomes hot enough to cause a major breakdown, frequently accompanied by fire.

To eliminate this potentially dangerous situation, which occurs anytime there is a leak of

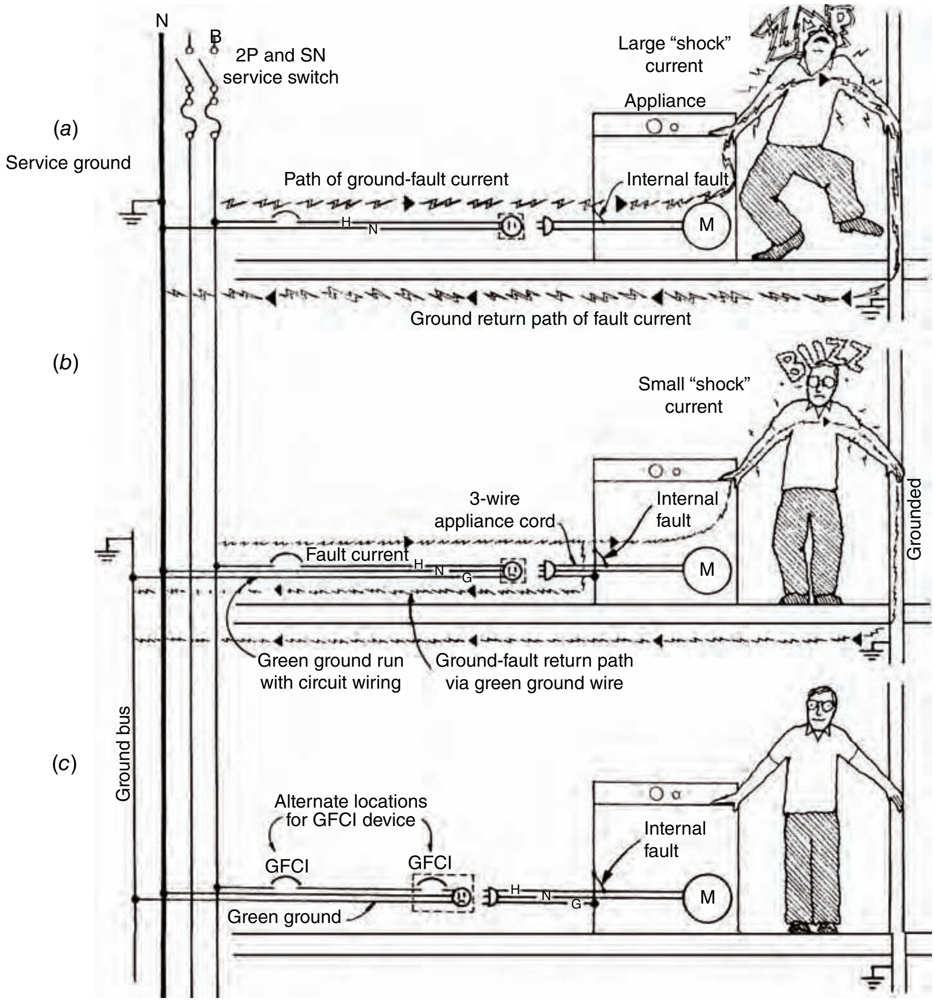


Fig. 29.10 *Three types of circuit arrangements. (a) A 2-wire, grounded-neutral circuit with no means of preventing shocks from ground faults. (b) A similar arrangement that includes a green ground wire, which considerably lessens the danger of ground-fault shocks. Note, however, that as long as the ground-fault current is below the rating of the branch circuit protective device (i.e., below 15 to 20 A), it will continue to flow within the appliance, causing overheating, arcing, and eventual destruction of the appliance. (c) GFCIs are mandatory for bathrooms, outdoor locations, swimming pool circuits, and other areas where ground faults are common and particularly hazardous.*

current to ground in an electric circuit, the ground-fault circuit interrupter (GFCI) was developed (Fig. 29.10*c*). This device compares, with extreme precision, the current flowing in the hot and neutral legs of a circuit; if there is a difference, it indicates a ground fault and the device trips out. The rapidity of this action—approximately one-half second—eliminates the possibility of a potentially dangerous shock hazard, which exists even in a properly grounded circuit, as in Fig. 29.10*b*, and all the more so for the circuit arrangement in Fig. 29.10*a*. The separate ground path required by the *NEC* (bonded metallic conduit system, green-ground, or both) serves to minimize the shock current taken by a person before the GFCI operates. The device can be applied at the panel to replace a normal circuit breaker (see Fig. 27.19*b*) or at an individual outlet to replace a normal receptacle device. See the *NEC* for locations where GFCI use is mandatory, such as outdoors and in kitchens and bathrooms. It is advisable to use GFCI devices on all appliance circuits. Application to lighting circuits is generally not required because fixtures are usually out of reach and are switch-controlled. In mixed lighting and receptacle circuits, a GFCI is best applied at the outlet that is to be protected.

29.5 ENERGY CONSERVATION CONSIDERATIONS

Before proceeding with a detailed description of design procedures, the many energy conservation ideas and techniques applicable to electrical distribution systems should be surveyed. This is done to provide focus on this important aspect of design, as individual techniques appear throughout the lengthy design procedure discussion and may be overlooked. The following recommendations are intended to assist with meeting a design intent to conserve energy.

1. Establish an energy budget based upon projected loads and normal operations; then, set an energy reduction figure of 10% to 20% and meet this goal by using the specific techniques that follow. Annual energy consumption estimates are best made with the aid of one of the many computer programs available for this purpose.
2. Learn to recognize the energy-use characteristics of all equipment and systems specified (see Table 29.7). In general, select high-efficiency equipment (motors, transformers, etc.). If these are not identified as such, use materials and equipment with the lowest temperature rise, because these have the lowest losses. This generally indicates the selection of choice. When comparisons are close, a detailed analysis may be necessary. Economic justification can be established with a life-cycle cost analysis. To avoid making a detailed cost analysis on every item, utilize one of the many available shortcut calculations for payback time (see Appendix J).
3. Provide electric load control equipment (demand control) either as part of an overall building control system or separately (see Sections 26.14 and 17.3).
4. In any multitenant residential building, provide individual user metering. Metering of heating and cooling energy should be part of the HVAC contract. All tenants should be made financially responsible for the energy they use. Exceptions to this rule would be made in the case of hotels, dormitories, and other transient facilities.
5. Where a choice of service voltages is available, consider the highest available. Similarly, consider the highest voltage in each class for interior distribution systems. This means 480 V in the 600-V class, 4 kV in the 5-kV class, and 13 kV in the 15-kV class. The result will be lower line losses, smaller panelboards at the branch circuit level, and generally a lower electrical contract cost (see Section 29.3).
6. In any building, the maximum total voltage drop *shall not* exceed 3% in branch circuits or feeders, for a total of 5% to the farthest outlet, based on steady-state design load conditions.
7. Avoid the use of electric heating elements if alternatives are available. Electric heat is an inefficient use of natural resources because of the low overall efficiency of fuel-to-electricity conversion.
8. Provide metering points (for fixed or plug-in meters) throughout the system to permit accurate analysis of power and energy use. Meters, both instantaneous reading and recording types, provide essential data regarding equipment loading, load patterns, load coincidence, power factor, load voltage, power demand, and energy consumption. Analysis of these data can indicate how to program and shift loads for maximum operational efficiency and lowest energy cost. A flexible design that permits such load shifting is assumed (see item 10).
9. Include provisions for power-factor correction in the system, both at devices and at the feeder level. Then, if metering (see item 8) indicates the necessity, add capacitors as required. High power factor reduces line losses, permits maximum utilization of equipment capacity, and avoids utility penalty charges. Utilization equipment rated greater than 1000 W and lighting equipment greater than 15 W, with an inductive reactance load component, should have a power factor of not less than 85% under rated load conditions. Utilization equipment

with an inherent power factor of less than 85% should be corrected to at least 90% under rated load conditions.

10. Size equipment as closely as possible to match the load. This normally results in improved efficiency and a higher power factor. Where load varies considerably—for example, between day and night or on weekends—consider splitting the loads so that part of the equipment can be switched off when the load is low, and the remaining load can be fed from a "night/weekend" feeder. Such a design allows the shutdown of whole systems rather than operating at a very low load with the associated high losses and low power factor. The design must be sufficiently flexible to permit shifting of loads between feeders if measurements on the facility in operation indicate that this is desirable (see item 8). The aim is to operate equipment as closely to the rated load as possible and to deenergize lightly loaded sections by shifting load to other, partly loaded equipment.
11. Use the most efficient type of control. This means solid-state controls for motors, variable-voltage, variable-frequency (VVVF) controls for variable-speed equipment (which should be considered for all variable building loads), remote switch controls for blocks of lighting, electronic control systems for elevators, and so on.
12. Arrange automatic time controls for equipment that is only needed for part of the day (such as ventilation fans, water coolers, vending machines, and computers) that might otherwise be active for 24 hours.
13. Seal all electric riser shafts to avoid heat loss by stack effect.
14. Generally select the coolest possible locations for electric equipment. Low ambient temperature (below 40°C [104°F]) permits the use of smaller equipment for the same load, with resultant lower cost and losses. If below-grade space is available, it is well suited for this purpose.
15. Provision for future expansion should be made by means of a design that accommodates additional equipment in lieu of oversizing equipment initially. Here again, the higher cost of two pieces of equipment can normally be justified by a detailed owning-and-operating (life-cycle) cost analysis using realistic cost escalation and capital cost figures.
16. Energy-conservation techniques for lighting and lighting control are found in Sections 16.17 and 17.3.
17. Energy conservation techniques for vertical transportation are found in Section 32.44 .

29.6 ELECTRICAL WIRING DESIGN PROCEDURE

The steps involved in the electrical wiring design of any facility are outlined in this section. These steps may in some instances be performed in a different order, or two or more steps may be combined, but the procedure normally used is the following:

1. Make an electrical load estimate based upon the areas involved, available building data, and any other pertinent information (see Section 29.2).
2. In cooperation with the local electric utility, decide upon the point of service entrance, type of service run, service voltage, metering location, and building utilization voltage (see Sections 27.1 to 27.11 and Section 29.5, item 5).
3. Determine, with the active input of the client, the proposed usage of all areas and information about all client-furnished equipment (including specific electric ratings and service connection requirements).
4. Determine from other consultants (such as those dealing with HVAC, plumbing, elevators, kitchens, and the like) the exact electrical ratings for all the equipment within their realm of design. This determination is often made after conferences during which the electrical consultant makes valuable recommendations to these other specialists about the comparative characteristics and costs of equipment (see Section 29.5, items 2, 7, 9, and 10). Such timely sharing of expertise is the foundation of the integrated building design process.
5. Determine the location and estimate the size of all required electric equipment spaces

including switchboard rooms, emergency equipment spaces (or areas), electric closets, and so forth. Panelboards are normally located in closets but may be located in corridor walls or elsewhere. These decisions are necessary early in the design process to enable the architect to reserve the appropriate spaces (in appropriate locations) for electrical equipment. Once the design is developed in detail, the estimated space requirements can be checked and necessary adjustments made.

6. Design the lighting for the facility. This step is complex and involves continued interaction between the architect and the lighting designer. Coordination between daylighting and electric lighting systems is especially critical.
7. Depending upon the type of facility, it may be necessary to separate the lighting plans from the plan(s) for other devices such as signaling, low-voltage systems, and receptacles. When an underfloor wiring system is used, it is customary to show it on a separate plan to avoid clutter and confusion. A decision about drawing conventions is made at the preliminary design stage by the project engineer. Once the decision has been made as to how this is to be handled, the lighting fixture layout can be made.
8. On the plan(s), locate all electrical apparatus including receptacles, switches, motors, and other power-consuming equipment. Underfloor, under-carpet, and over-ceiling wiring and raceway systems would be shown at this stage, generally on a separate plan.
9. On the plan(s), locate data-processing and signal apparatus such as telecommunication outlets, network connections, phone outlets, speakers, microphones, TV outlets, fire and smoke detectors, and so on. At this stage, provision is also made for load control wiring, building automatic control wiring, computer control, and the like. The decision is also made as to whether intelligent panels will be used (see Section 27.23). Because some of these systems may be covered by separate contracts, the division of responsibility must be clearly defined. Often, only an empty conduit system and power outlets or sources are required in the electrical work contract. The information in this chapter deals only with wiring design; further discussion of signal equipment is reserved for Chapter 31.
10. Circuit all lighting devices and power equipment to the appropriate panels and prepare the panel schedules. Include in this step the circuitry for emergency equipment.
11. Compute panel loads.
12. Prepare a riser diagram. This includes the design of distribution panels, switchboards, and service equipment.
13. Compute feeder sizes and all protective equipment ratings.
14. Check the preceding work.
15. Coordinate the electrical work with the other disciplines and with the architectural plans. This is not really a separate step, but rather a continuing process starting at step 9 and covering all subsequent stages of the work.

The background for items 1, 2, 3, 4, 6, 7, and 9 is covered elsewhere in this book. The remaining steps, that is, 5, 8, 10, 11, 12, 13, and 15, are discussed in order in the following sections.

29.7 ELECTRICAL EQUIPMENT SPACES

The spaces required for electrical equipment in a facility vary greatly, depending upon the design and the nature of the building. The working spaces required around major pieces of electrical switchgear and transformers were discussed previously (see Fig. 27.26). The *NEC* (in Article 110) further specifies the minimum working space required in front of electrical equipment.

(a) Residences

In private residences, the service equipment and the building panelboard are generally incorporated into a single unit. The main disconnect(s) is usually installed as the main switch/breaker of the panel. A number of typical residential service-panel arrangements are shown in Fig. 29.11. The panel is normally placed in the garage, utility room, or basement. To minimize voltage drop, the panel should be placed as close to the major electrical loads as practical, without sacrificing valuable space or making the panel inaccessible. Frequently, a smaller

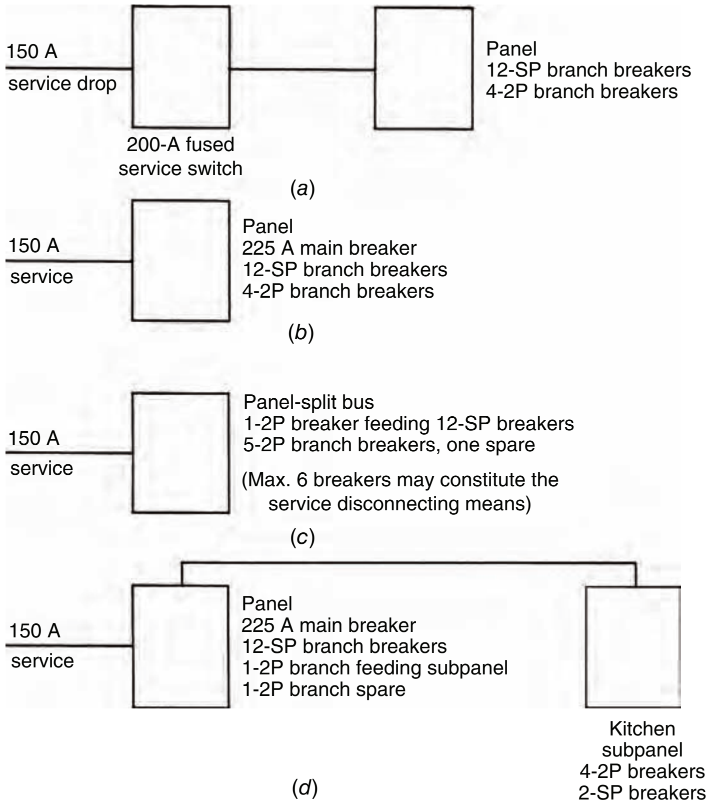


Fig. 29.11 *Typical 150-A service arrangements, applicable to residences and small commercial buildings. The service switch can be a separate unit (a) or combined with the branch circuit panelboard (b–d). The panel may be a single unit (a, b), two units in a single enclosure, fed by separate service switches (c), or a central panel and a subfed single-use panel (d)—in this case, a kitchen subpanel.*

panel can be subfed from the main panel to feed the kitchen and laundry loads. In apartments, panels are normally placed in the kitchen or the corridor immediately adjoining the kitchen. This location is chosen so that the panel circuit breaker can act as the required disconnecting means for most fixed appliances (see *NEC* Article 422III).

(b) Commercial Spaces

The location of the required panelboards depends upon their type and number and upon availability of space. In the example research building (for which Fig. 29.12 is a partial plan), lighting panels are recessed into the corridor wall because the building is only two stories high, and the panels can be vertically stacked and fed by a single conduit. If this building were six or more stories high, an electric closet (see Section 29.8) would be advisable to accommodate the panel and riser conduits. When panels are installed in finished areas such as corridors, flush mounting is required.

To limit the voltage drop on a branch circuit in accordance with code requirements, panelboards should be located so that no circuit exceeds 100 ft (30 m) in length. If 15-A or 20-A branch circuits longer than this are unavoidable, No. 10 AWG wire should be used for runs of 100 to 150 ft (30–46 m) and No. 8 AWG for longer circuits. These circuits are normally wired with No. 12 AWG wire.

The laboratory between the two offices of Fig. 29.12 is intended to function as a self-contained unit and is therefore equipped with its own panel. Multioutlet assemblies, all wiring within the room,

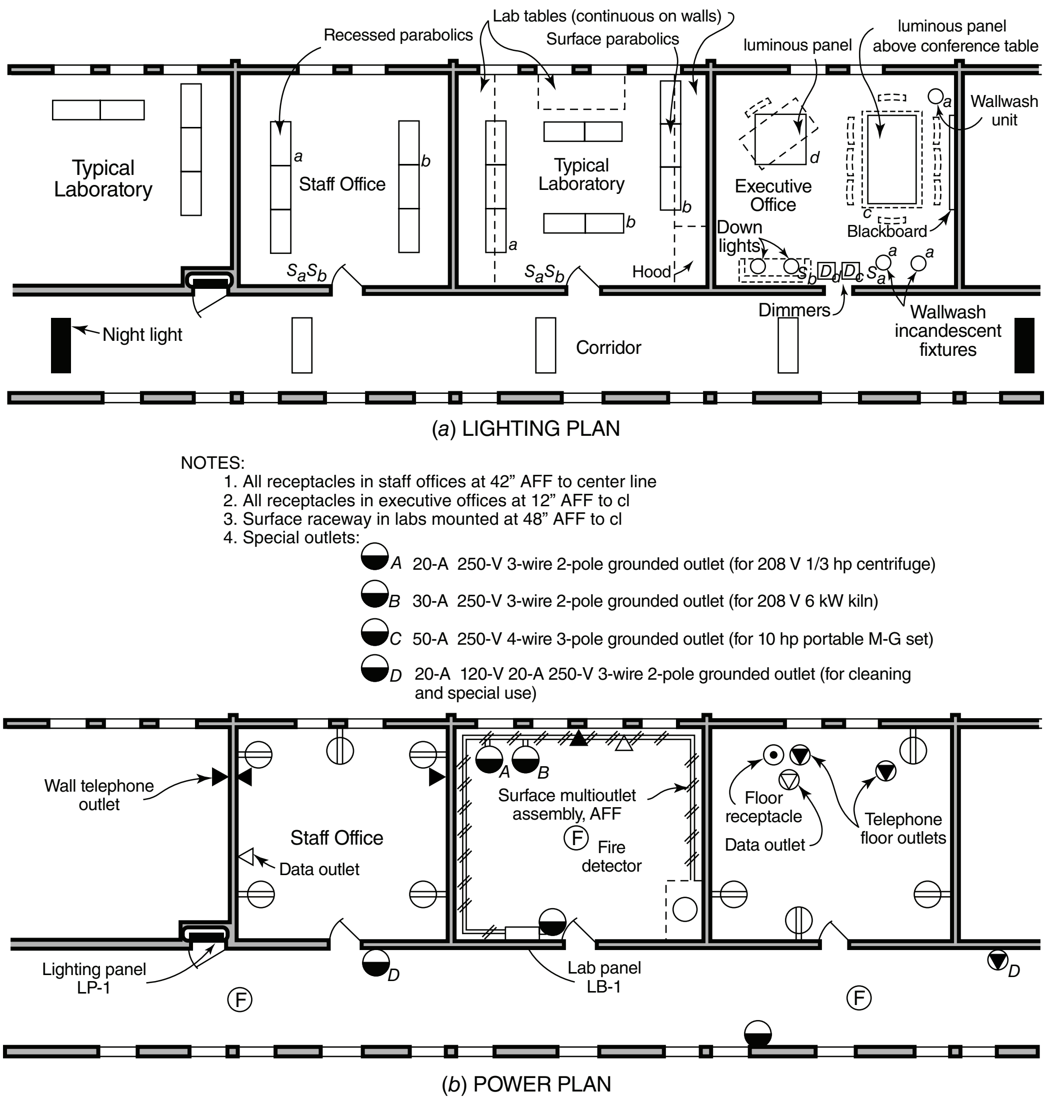
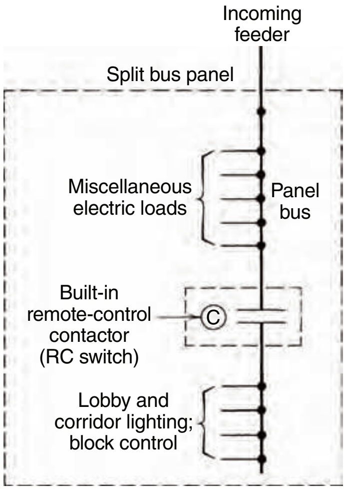


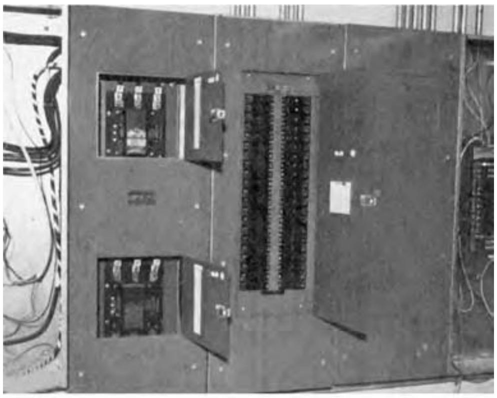
Fig. 29.12 *Typical floor plans for lighting and power for a section of an office–laboratory building. Separate lighting (a) and power (b) plans are drawn for the sake of clarity. For circuited plans, see Figs. 29.21 and 29.22. Data outlets handle data-processing and telecommunications cabling.*

and the panel itself are surface-mounted to allow ready access to all components in order to accommodate the frequent rewiring encountered in laboratories. A main circuit breaker should be provided in such a panel to act as a main disconnect, whether required by code or not. Where panels are convenient to the load controlled, the panel circuit breakers may be used for switching.

Panels supplying large blocks of load simultaneously switched, such as auditorium house lighting, lobby lighting, large single-use office areas, store lighting, and the like, can be constructed with built-in electrically operated, mechanically held contactors to switch the entire load, with control at any desired remote location. These remote-control (RC) switches are discussed in Section 27.15. If only part of the panel circuits are so arranged (i.e., for remotely controlled block switching), a split bus panel can be used, with the RC switch controlling only that part of the panel load (Fig. 29.13).



(*a*)



(*b*)

Fig. 29.13 *(a) Single-line diagram of a split bus panel. This design is used when a block of load is to be controlled as a unit. The control point is either remote, at the panel, or both. The contactor (RC switch) is electrically operated and mechanically latched. (b) RC switches (mechanically held contactors) are shown to the left of a bank of panels. The contactors were installed to provide photocell and timer control of department store lighting. (Photo courtesy of Automatic Switch Co.)*

Small offices, stores, and other small buildings frequently have lighting panels mounted in a convenient finished area and utilize the panels' circuit breakers for load switching. In large buildings, strategically located electric closets are provided to house all electrical supply equipment. Power panels and distribution panels are located as required by the loads fed through them.

In general, branch circuit panels, distribution panels, and switchboards are best located near the electrical load center. This minimizes feeder length and reduces voltage drop, making it the most economical arrangement.

Every completely enclosed switchgear room, emergency generator room, or transformer vault should be equipped with an emergency light source (see Section 17.31). In generator rooms, these should be battery-operated to give illumination for generator repairs in the event of generator failure during a power outage.

29.8 ELECTRICAL CLOSETS

When designing a building electric system, particularly for multistory construction, it is often advantageous and convenient to group the electrical equipment in a small room called an *electrical closet* (Fig. 29.14). The shape of this space can be varied to fit the architectural requirements, and it should provide the following:

1. One or more locking doors.
2. Vertical stacking, above and below other electric closets, and located so as not to block conduits entering or leaving horizontally. Thus, locations on outside walls and adjoining shafts, columns, and stairs are poor choices.
3. Space free of other utilities such as piping or ducts passing through the closet, either horizontally or vertically.
4. Sufficient wall space to mount all requisite and future panels, switches, transformers, telephone cabinets, and communication equipment. Wall cabinet space must be coordinated with raceway connections to underfloor ducts and over-the-ceiling raceway systems (see Sections 28.24 to 28.30).
5. Floor slots or sleeves of sufficient size for all present and future conduit or bus risers.
6. Sufficient floor space so that an electrician can work comfortably and safely on initial installation and repair.
7. Adequate illumination and ventilation.

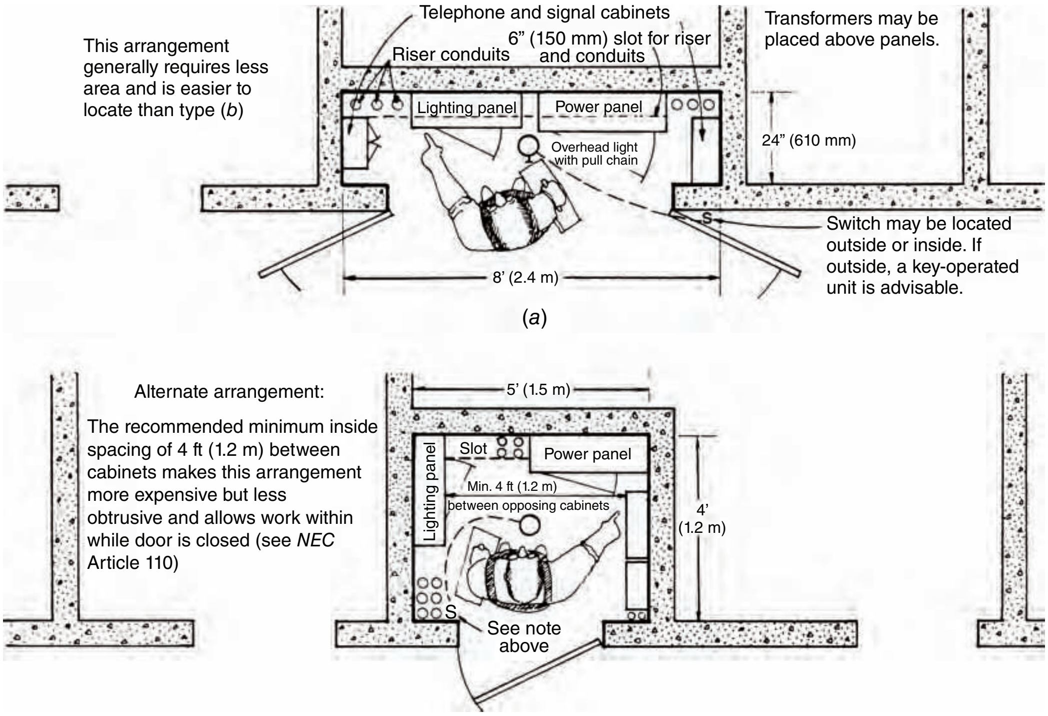


Fig. 29.14 *Typical electric closets with some of the usual equipment. If warranted due to the amount of equipment, separate closets may be used for signal and telephone conduits and cabinets. Smaller spaces may be used, depending upon the types of equipment cabinets and their arrangement (see* NEC *Article 110). In all cases, sufficient space must be provided to allow full opening of all cabinet doors. Empty wall space for future cabinets and equipment should also be considered.*

29.9 EQUIPMENT LAYOUT

Wiring devices, principally receptacles and switches, are located on electrical plans as required by the equipment and by the anticipated use of an area.

Switches for control of lighting or receptacles are normally placed on the strike side of a door. Other devices, such as plug-in strips on walls and special-purpose receptacles, are shown and identified. Signal outlet locations are often noted but generally remain uncircuited on floor plans, a riser or floor raceway plan being utilized to show interconnections. Signal devices include fire-alarm equipment, telephone and intercom equipment, data and communications, radio and TV outlets, and so on. These devices may be identified by a special symbol or note where a standard symbol is not available.

As mentioned previously, lighting fixture outlets are normally placed on the same drawing as wiring devices unless the large number of the latter precludes showing the lighting without unduly complicating the drawings. In such an event, the lighting is shown on one drawing and receptacles on another, with signals shown on the one less cluttered. A ceiling or underfloor wiring system would necessitate such separation. Motors, heaters, and other fixed and permanently wired equipment are shown and identified on the receptacle drawings (also called *power drawings*, in contrast to lighting drawings). Equipment furnished with a cord and plug is not normally shown. However, the receptacle intended for supplying such a device is shown and identified. An abbreviated symbol list is given in Fig. 29.15.

29.10 APPLICATION OF OVERCURRENT EQUIPMENT

Before beginning an explanation of circuiting, it is necessary to explain the principles underlying overcurrent protection. As outlined in Chapter 27, the

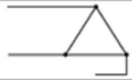
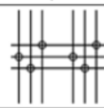
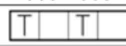
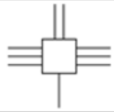
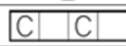
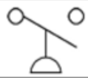
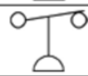
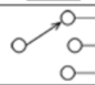
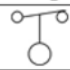
MF NO	DESCRIPTION	TYPE	SYMBOL
DIV 26	ELECTRICAL		
26 00 00	electrical, delta connection	I	
26 00 00	electrical, motor, single-phase	I	
26 00 00	electrical, motor, three-phase	I	
26 00 00	electrical, transformer, one-line diagram	I	
26 00 00	electrical, transformer, plan	I	
26 00 00	electrical, wye connection	I	
26 05 00	electrical, duct, cell floor header	I	
26 05 00	electrical, duct, trolley	I	
26 05 00	electrical, duct, underfloor junction box	I	
26 05 00	electrical, earth ground	I	
26 05 00	electrical, junction box	I	
26 05 00	electrical, ladder cable tray	I	
26 05 00	electrical, panelboard, home run to (arrowheads indicate the number of circuits)	I	
26 05 00	electrical, pressure switch-close on increase	I	
26 05 00	electrical, pressure switch-open on increase	I	
26 05 00	electrical, pull box	I	
26 05 00	electrical, switch, multiposition	I	
26 05 00	electrical, switch, normally closed float	I	
26 05 00	electrical, switch, normally closed foot operated	I	
26 05 00	electrical, switch, normally closed limit	I	

Fig. 29.15 *Selected electrical symbols from the United States National CAD Standard® - v5. (Reproduced with permission of the buildingSMART alliance; © National Institute of Building Sciences. Refer to the Standard for the full array of electrical and other symbols.)*

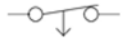
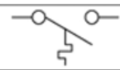
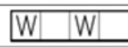
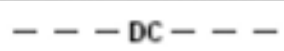
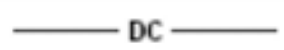
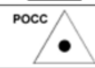
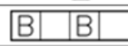
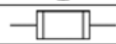
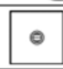
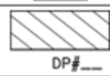
MF NO	DESCRIPTION	TYPE	SYMBOL
DIV 26	ELECTRICAL		
26 05 00	electrical, switch, normally closed temperature activated	I	
26 05 00	electrical, switch, normally closed time delay	I	
26 05 00	electrical, switch, normally open float	I	
26 05 00	electrical, switch, normally open limit	I	
26 05 00	electrical, switch, normally open temperature activated	I	
26 05 00	electrical, switch, normally open time delay	I	
26 05 00	electrical, switch, single break	I	
26 05 00	electrical, wireway	I	
26 05 00	direct current underground = DC; thin dash line, 2.5mm (3/32") text	L	
26 05 00	direct current aboveground = DC; thin line, 2.5mm (3/32") text	L	
26 05 00	rigid conduit line = RC; thin line, 2.5 mm (3/32") text	L	
26 09 00	electrical, meter	I	
26 10 00	electrical, substation	I	
26.11.00	electrical, interconnection with substation, aboveground	I	
26.11.01	electrical, interconnection with substation, underground	I	
26 20 00	electrical, busway	I	
26 20 00	electrical, floor outlet, data communication	I	
26 20 00	electrical, fuse with rating	I	
26 20 00	electrical, normally closed relay contact	I	
26 20 00	electrical, normally open relay contact	I	
26 20 00	electrical, outlet, data communication	I	
26 20 00	electrical, push button	I	
26 24 00	electrical, distribution panel	I	

Fig. 28.15 *(Continued)*

function of an overcurrent device is to open (interrupt) a circuit when the current rating of the equipment being protected is exceeded. All equipment must be protected in accordance with its current-carrying capacity. Where ratings do not correspond exactly, the next larger standard size for protective devices up to 800 A may be used; above this, use the next lower rating (see *NEC* Article 240 for further restrictions). The following general rules govern the application of overcurrent protection:

1. Overcurrent devices must be placed on the line or supply side of the equipment being protected (Fig. 29.16).
2. Overcurrent devices must be placed on all *ungrounded* conductors of the protected circuit.
3. In general, conductor sizes shall not be reduced in a circuit or tap unless the smallest-size wire is protected by the circuit overcurrent devices (Fig. 29.17).
4. Overcurrent devices shall be located so as to be readily accessible.

29.11 BRANCH CIRCUIT DESIGN

A branch circuit, by *NEC* definition, refers only to the circuit conductors, although for our purposes and in trade parlance it includes the protective device and the outlets served. Such circuits may be the multioutlet general-purpose type (Fig. 29.18*a*), the multioutlet appliance type (Fig. 29.18*b*), or the single-outlet type intended for a specific piece of equipment (Fig. 29.18*c*). The multioutlet types are limited to 50 A in capacity, whereas the single-outlet type is governed in size only by the requirements of the item being served and may be 200 A or 300 A in size.

In its simplest form, a branch circuit comprises only two circuit wires. However, multiwire branch circuits carrying 2- to 3-phase wires plus a neutral are also widely used. Generally, each branch circuit should be sized for the load connected to it plus the load expansion that is expected. These general rules of good practice should be followed:

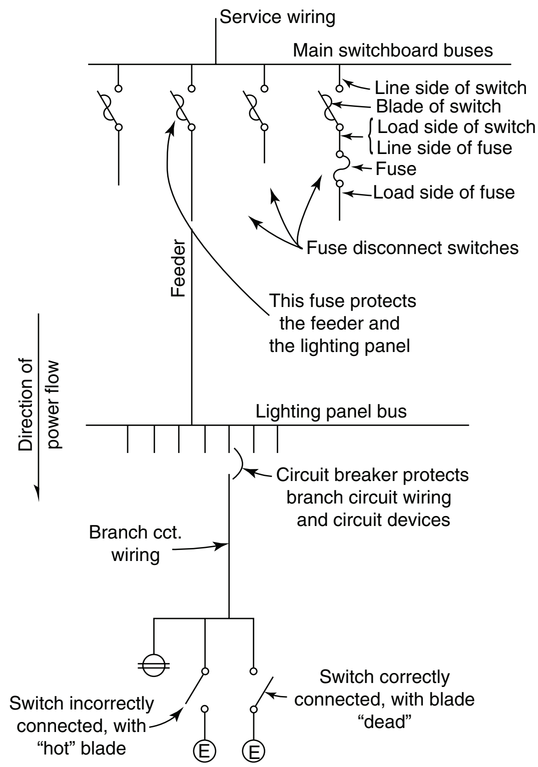


Fig. 29.16 *Location of overcurrent protective equipment. Protective equipment should always be located at the point where the conductor receives its source of supply so that when the protective device operates, the current supply is cut off.*

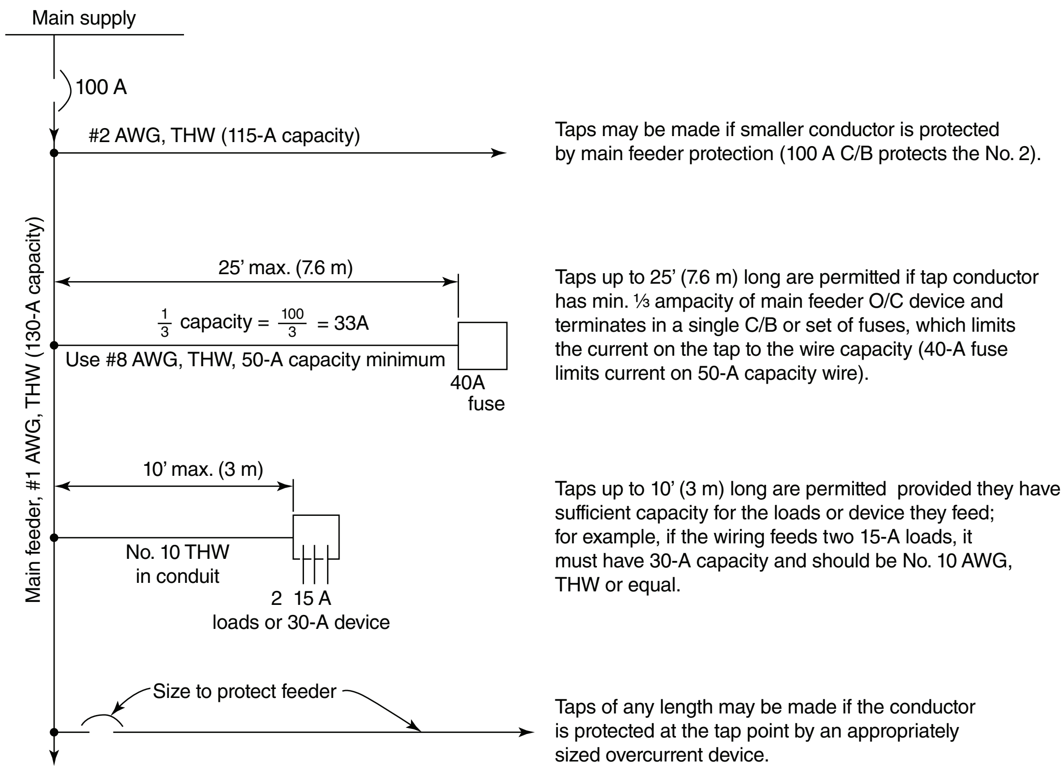
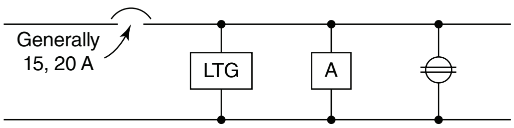


Fig. 29.17 *Some permissible tap arrangements. See* NEC *Article 240 for restrictions on taps in addition to those given in the figure.*

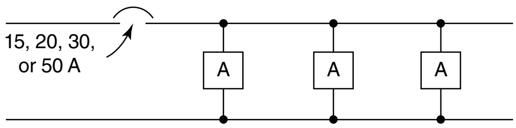
1. In all but the smallest installations, connect lighting, convenience receptacles, and appliances on separate (groups of) circuits, although this is not an *NEC* requirement.
2. General-purpose branch circuits should be 20 A and wired with No. 12 AWG wire. Switch legs may be No. 14 AWG if the lighting load permits and the wiring meets the tap requirements of *NEC* Article 240.
3. Limit the circuit load on 15-A and 20-A circuits to the values shown in Table 29.5. This provides the required building load expansion capability in the branch circuitry; that is, bringing the loads on the branch circuits up to maximum allows additional building loads to be absorbed. Because it is not always economical or feasible to expand existing circuits, however, panels are always equipped with spare breakers. These can also be utilized to pick up building load expansion, or the user may use a combination of the two techniques, expanding some existing circuits and adding new ones. (See Section 29.15 for a discussion of this subject.)

Because lighting and specific devices are circuited according to their nameplate ratings, the only circuitry item left to the judgment of the designer is the number of convenience receptacles per circuit. The *NEC* specifies that plug outlets (convenience receptacles) be counted, in totaling loads, at 1.5 A each unless included in the load for general lighting. This point requires some clarification. The receptacle load for general illumination in dwellings is included in the 3 V-A/ft^2 (32.3 V-A/m^2) specified by *NEC* Table 220-12 and found in Table 29.1. This is because receptacle outlets on general illumination circuits are assumed to supply illumination (i.e., lamps), and are therefore necessarily included in the lighting load. Application of the 1.5-A (180-V-A) per outlet criterion to such outlets would, in the opinion of the *NEC*, unnecessarily limit the number of outlets permitted on such circuits.

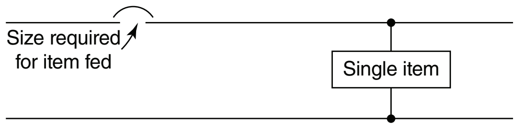
The same is true for appliance circuits. On both of these types, according to the *NEC*, the number of receptacle outlets is not limited. On 15- and 20-A receptacle circuits, which are neither general illumination nor small appliance branch



(*a*) General-purpose branch circuit. Supplies outlets for lighting and appliances, including convenience receptacles.



(*b*) Appliance branch circuit. Supplies outlets intended for feeding appliances. Fixed lighting not supplied.



(*c*) Individual branch circuit, designed to supply a single specific item.

Fig. 29.18 *Branch circuit types. See* NEC *Article 210 for detailed descriptions.*

circuits, the number of outlets is limited to 10 (1800 V-A) on a 15-A circuit and 13 (2340 V-A) on a 20-A circuit by applying the 1.5-A per outlet criterion.

It appears that the distinction between circuit types is not completely clear, and that good practice dictates the limitation of convenience receptacles per circuit to a considerably smaller number. Thus, following the guidelines of Table 29.5 of 9- and 12-A loading on 15- and 20-A circuits, respectively, this approach would yield

$$\text{15-A circuit:} \quad \frac{9\ \text{A}}{1.5\ \text{A per outlet}} = 6\ \text{outlets per circuit}$$

$$\text{20-A circuit:} \quad \frac{12\ \text{A}}{1.5\ \text{A per outlet}} = 8\ \text{outlets per circuit}$$

These values must be used judiciously. If the devices to be energized are small, these quantities may be used. Such would be the case in a business office, where only an electric pencil sharpener or a desk lamp (100 V-A) would be plugged in. However, for computer-equipped offices, service and repair facilities, and the like, plan for no more than four receptacles on a 20-A circuit—and preferably two or three receptacles maximum on a 15-A circuit. Of course, diversity of use is an all-important factor, and the more accurately it can be estimated, the better the design result.

A further note of caution is in order: receptacles should be arranged, if at all possible, so that the loss of a single circuit does not deprive an entire area of power. That is, for the sake of reliability, circuitry should be alternated to give each space access to parts of different circuits.

NEC Table 210-24 specifies certain requirements for conductors, devices, and loads permissible

TABLE 29.5 Recommended Branch Circuit Loads[a]

Size Circuit	Circuit[d] Amperes	Volt-Amperes[d] at 120 V	Volt-Amperes at 277 V
0% Expansion[b, c]			
15 A	12	1440	—
20 A	16	1920	4440
25% Expansion[e]			
15 A	9.6	1150	—
20 A	12.8	1520	3600
50% Expansion[f]			
15 A	8	960	—
20 A	11	1300	3000

[a]The loading shown will provide the specified expansion in the branch circuits. Where branch circuit expansion is not practical, the required expansion can be obtained from panel spares.

[b]See Table 29.1 for anticipated load growth.

[c]For 0% expansion, initial load = 80% of the circuit rating, which is the maximum permissible for continuous loads. See Table 29.6, note 6.

[d]For branch circuits feeding utilization equipment such as air conditioners in addition to convenience outlets, see *NEC* Article 210-23.

[e]To accomplish 25% expansion, the circuit is derated to 80%, i.e., 80% of 12 A = 9.6 A, etc.

[f]To accomplish 50% expansion, the circuit is derated by ⅓, i.e., two-thirds of 12 A = 8 A, etc. (Then 50% expansion on 8 A yields 12 A.)

TABLE 29.6 Branch Circuit Requirements

	Branch Circuit Size				
	15 A	**20 A**	**30 A**	**40 A**	**50 A**
Minimum-size copper conductors	No. 14	12	10	8	6
Minimum-size taps	No. 14	14	14	12	12
Overcurrent device rating	15 A	2s0	30	40	50
Lampholders permitted	Any type	Any type	Heavy duty	Heavy duty	Heavy duty
Receptacle rating permitted (see note 7)	15 A	15 or 20	30	40 or 50	50
Maximum load (see notes 6 & 8)	15	20	30	40	50

Notes:

1. Wiring shall be types RHW, RHH, T, THW, TW, THWN, THHN, XHHW in raceway or cable.
2. On a 15-A circuit, the maximum single appliance shall draw 12 A. On a 20-A circuit, the maximum single appliance shall draw 16 A. If combined with lighting or portable appliances, any fixed appliance shall not draw more than 7.5 A on a 15-A circuit and 10 A on a 20-A circuit.
3. On a 30-A circuit, maximum single appliance draw shall be 24 A.
4. Heavy-duty lampholders are units rated not less than 750 W.
5. 30-, 40-, and 50-A circuits shall not be used for fixed lighting in residences.
6. When loads are connected for long periods (3 hours or more), the actual load shall not exceed 80% of the branch circuit rating. Conversely, continuous-type loads shall be figured at 125% of the actual load in all load calculations.
7. A single receptacle on an individual branch circuit shall have a rating not less than the circuit—for example, 15 A on a 15-A circuit. Also, 15-A receptacles on a 20-A circuit shall not supply a load greater than 12 A for appliances; 20-A receptacles on a 20-A circuit shall be limited to a 16-A load.
8. Rating of a single piece of cord-connected utilization equipment shall not exceed 24 A when connected to a 30-A circuit.
9. For additional restrictions and data on branch circuit use and application, see *NEC* Table 210-24.

on general-purpose branch circuits. These are excerpted and summarized in Table 29.6.

29.12 BRANCH CIRCUIT DESIGN GUIDELINES: RESIDENTIAL

1. The *NEC* requires for residences sufficient circuitry to supply a load of 3 V-A/ft^2 (32.3 V-A/m^2) in the building, excluding unfinished spaces such as porches, garages, and basements. Using Table 29.5, which already includes a 20% derating of circuits to provide for continuous loading, this works out to 480 ft^2 (45 m^2) on a 15-A circuit (1440 V-A) and 640 ft^2 (60 m^2) on a 20-A circuit (1920 V-A). Allowing for some expansion, such as a finished basement or enclosing a porch to expand the living area, results in a good-practice recommendation of 400–480 ft^2 (37–45 m^2) per 15-A circuit and 530–640 ft^2 (49–60 m^2) per 20-A circuit.

   These good-practice figures normally provide enough circuits for all but the most heavily loaded residences. If actual design analysis, considering the owner's project requirements, indicates the need for additional circuits, however, they clearly must be provided.
2. The *NEC* (Article 210-11) requires a minimum of two 20-A appliance branch circuits (Fig. 29.18*b*) to feed all the receptacle outlets in the kitchen, pantry, breakfast, and/or dining room and similar areas, and *only* these outlets. This is because any receptacle in these areas is a potential appliance outlet and must be fed and circuited as such. Permanently installed appliances such as a food disposal, dishwasher, fan hood, and the like may *not* be connected to these appliance circuits. An exception is made to permit clock outlets to be fed from these circuits. Furthermore, the *NEC* requires that all kitchen outlets intended to serve countertop areas must be fed from at least two of these appliance circuits (these circuits may also feed appliance outlets in the other spaces specified previously). Thus, not all countertop workspace will be deenergized by the failure of a single circuit.

   Although the code does not limit the number of appliance outlets to be wired into each circuit, good practice dictates that these

receptacles be circuited with no more than four such outlets per 20-A circuit. This in turn usually requires more than the code minimum of two appliance circuits. Among other requirements, the *NEC* states that for kitchen and dining areas:
- No point on a wall behind a countertop shall be more than 24 in. (610 mm) from an outlet.
- All countertop convenience receptacles shall be of the GFCI type.

3. Locations utilized primarily or frequently for workshop-type activities, such as garages, utility rooms, and basements, should be provided with receptacles wired in appliance-type circuits (i.e., 20-A receptacles on 20-A circuits), with no more than four such receptacles to a circuit. Receptacles in garages, sheds, crawlspaces, below-grade finished or unfinished basements, and outdoors must be of the GFCI type. (For exceptions to this GFCI rule, see *NEC* Article 210-8.)
4. Additional circuits similar to appliance circuits (no fixed lighting outlets) should be furnished to supply one outlet in each bedroom of a house that is not centrally air-conditioned. Such outlets are intended for window air conditioners. (Good design practice may provide a window arrangement, attic ventilation, insulation, sunscreening, and the like, that can reduce the demand for these noisy energy users.)
5. The *NEC* requires that at least one 20-A appliance circuit supply the laundry outlets only. This requirement is good practice. If an electric clothes dryer is anticipated (and it should be, unless it is definitely known that a gas dryer will be used), an individual branch circuit (distinct from the laundry outlets circuit[s] and rated for the load) should be supplied to serve this load via a heavy-duty receptacle. (Facilities for hanging clothes should be provided for those who prefer not to consume electrical energy on this simple task.)
6. Lay out convenience receptacles so that no point on a wall is more than 6 ft (1.8 m) from an outlet. Use 20-A, grounding-type receptacles only. Do not combine receptacles and switches into a single outlet except where convenience of use dictates high mounting of receptacles.
7. Circuit the lighting and receptacles so that each room has parts of at least two circuits. This includes basements and garages.
8. Avoid placing all the lighting in a building on a single circuit.
9. Supply at least one 20-A wall-mounted receptacle adjacent to each bathroom lavatory (sink) location. Such receptacles must have GFCI protection. They should be fed from a 20-A circuit that energizes only such bathroom receptacles. Bathroom lighting, exhaust fan, heaters, or other outlets should not be connected to the bathroom receptacle circuit.
10. Provide at least two GFCI-protected and weatherproof receptacles on the outside of the house, one in front and one at the rear. Switch control of the outside receptacles from *inside* the house is a convenience.
11. In rooms without overhead lighting, provide switch control for one-half of a strategically located receptacle that is intended to supply a lamp (see Fig. 29.19 for the wiring arrangement in such a case).
12. Provide switch control for closet lighting. Pull chains are a nuisance (but are considerably cheaper).
13. In bedrooms, supply two duplex outlets at either side of the likely bed location to accommodate electric blankets, clocks, radios, lamps, and other such appliances.
14. A disconnecting means, readily accessible and within sight of the controlled item, must be provided for electric ranges, cooktops, and ovens. It is good practice to utilize a small kitchen panel recessed into a kitchen wall to control the large kitchen appliances and provide the required disconnecting means.

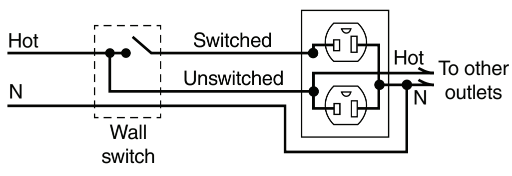


Fig. 29.19 *Split wiring of a duplex receptacle. The upper half is switch-controlled; the lower half is "hot" all the time. This allows wall switch control of a lamp or another device while keeping part of the receptacle live for independent use. Notice that the receptacle is mounted with the grounding pole at the top. This is the safest way to install receptacles because a metallic item such as a paper clip falling on an inserted cap will contact the ground pole only.*

15. Perimeter lighting, sensor control, and manual override can do much to lessen vandalism and discourage prowlers.
16. To accommodate the very rapidly increasing number of persons who work at home (either full- or part-time) every study and work room or, in their absence, every large master bedroom should be electrically equipped to double as a home office. This room or area should be supplied *minimally* with these electrical services:
    - Six duplex 15-A or 20-A receptacles connected to at least two different circuits, one of which should serve no other outlets. All of these receptacles should be equipped with appropriate surge suppression (see Section 27.37).
    - An additional separate insulated and isolated ground wire, connected only at the service point, should be run to the box(es) containing two of the receptacles required in the preceding point, and there terminated, clearly marked, and labeled. These grounds are intended for possible use with isolated ground (IG) receptacles, if it is found that the normal receptacles are too electrically noisy.
    - Two telephone jacks in recessed boxes should be provided in the area. In addition, an empty ¾-in. (19-mm) conduit from the telephone entry service point to an empty 4-in. (100-mm) square box in the area should be provided. An appropriate surge suppressor must be provided for the incoming telephone service lines.
    - For lighting design of this area, refer to the discussion on lighting for spaces with numerous computers in Chapter 16.

A tabulation of residential electrical equipment, including recommended circuit and receptacle descriptions, is shown in Table 29.7. A complete residential wiring plan for a small house is shown in Fig. 29.20. Although residential plans are frequently left uncircuited, a completely circuited layout is shown here for informational purposes. The plan does not show the electrical equipment recommended for a home office that is described in item 16 for two reasons:

1. The plan is so compact that there is no single preferable location for the numerous outlets required.
2. Adding the required outlets to any selected area would clutter the plan to the point of illegibility.

29.13 BRANCH CIRCUIT DESIGN GUIDELINES: NONRESIDENTIAL

(a) Schools

Because schools comprise an assembly of varied-use spaces, including instruction, lab, shop, assembly, office, and gymnasium, plus special areas such as swimming pools, photographic labs, and so on, it is not possible to generalize on branch circuit design considerations except for the following:

1. To accommodate the audio-visual equipment frequently used in classrooms, 20-A outlets wired two to a circuit should be placed at the front and back of each such room. A similar receptacle, wired six or eight to a circuit, should be placed on each remaining wall.
2. To accommodate fixed computers, a detailed layout of the space showing the proposed computer locations is required. A two-section surface-mounted or recessed raceway on the wall behind the computers should be provided. The power section should have two duplex 20-A receptacles at each computer station, wired on alternate circuits. The second section of the raceway is intended for low-voltage wiring, such as network cabling, and wiring to computer peripherals. Providing for good cable management can substantially improve the appearance and maintainability of this critical area.
3. Switching for lighting should provide:
    - High–low levels for energy conservation and to permit low-level lighting for screen viewing. With fluorescent lighting, this can be accomplished by alternate ballast wiring and switching, thus avoiding the high cost of dimming equipment. The multiple modes of classroom use must be considered when establishing switching scenarios.
    - Separate switching of the lighting fixtures on the window side of the room, which is often well lit by daylight. Control should be initiated automatically by a photocell (see Section 17.3).

TABLE 29.7 Load, Circuit, and Receptacle Chart for Residential Electrical Equipment

Appliance	Typical Connected Volt-Amperes[a]	Volts	Wires[b]	NEMA Circuit Breaker or Fuse, amp	Outlets on Circuits	Device[d] and Configuration (see Fig. 27.40)
KITCHEN						
Range[e, c, i]	12,000	115/230	3 #6	60	1	14–60R
Oven (built-in)[c, i]	4500	115/230	3 #10	30	1	14–30R
Range tops[c, i]	6000	115/230	3 #10	30	1	14–30R
Dishwasher[c]	1200	115	2 #12	20	1	5–20R
Waste disposer[c]	300	115	2 #12	20	1	5–20R
Microwave oven	1000	115	2 #12	20	1 or more	5–20R
Refrigerator[f]	300	115	2 #12	20	1 or more	5–20R
Freezer[f]	350	115	2 #12	20	1 or more	5–20R
LAUNDRY						
Washing machine	1200	115	2 #12	20	1	5–20R
Dryer[c, i]	5000	115/230	3 #10	30	1	14–30R
Hand iron[e]	1650	115	2 #12	20	1	5–20R
LIVING AREAS						
Workshops[e, j]	1500	115	2 #12	20	1 or more	5–20R
Portable heater[e]	1600	115	2 #12	20	1	5–20R
Television	300	115	2 #12	20	1 or more	5–20R
Audio center[g]	350	115	2 #12	20	1 or more	5–20R
DVD or VCR[g]	150	115	2 #12	20	1 or more	5–20R
Personal computer and peripherals[g, h]	1000	115	2 #12	20	1 or more	5–20R
FIXED UTILITIES						
Fixed lighting	1200	115	2 #12	20	1 or more	—
Air conditioner, ¾ hp (0.56 kW)[i,j]	1200	115	2 #12	20 or 30	1	5–20R 14–30R
Central air conditioner[c, i, j]	5000	115/230	3 #10	40	1	—
Sump pump[j]	300	115	2 #12	20	1 or more	—
Heating plant (i.e., forced-air furnace)[i,k]	600	115	2 #12	20	1	—
Attic fan[j]	300	115	2 #12	20	1 or more	5–20R

[a]Wherever possible, use the actual equipment rating.

[b]Number of wires does not include equipment grounding wires. Ground wire is No. 12 AWG for a 20-amp circuit and No. 10 AWG for 30- and 50-amp circuits.

[c]For a discussion of disconnect requirements, see *NEC* Article 422.

[d]Equipment ground is provided in each receptacle.

[e]Heavy-duty appliances regularly used at one location should have a separate circuit. Only one such unit should be attached to a single circuit at the same time.

[f]A separate circuit serving only one other outlet is recommended.

[g]Surge protection recommended.

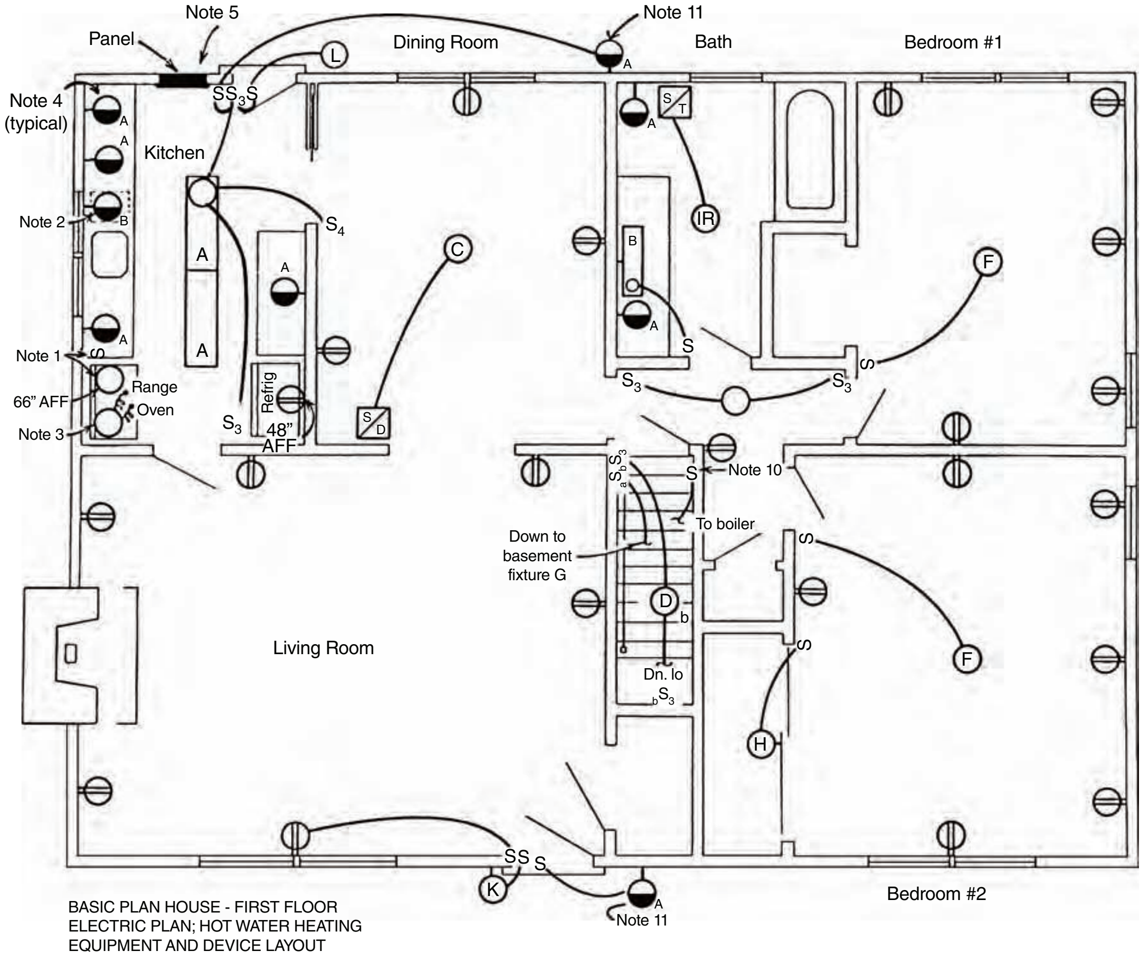
[h]Isolated ground may be required.

[i]A separate circuit is recommended.

[j]It is recommended that all motor-driven devices be protected by a local motor-protection element unless motor protection is built into the device.

[k]Connect through the disconnect switch equipped with a motor-protection element.

4. Provide appropriate outlets for all special equipment in labs, shops, rooms with cooking activities, and the like.
5. Use heavy-duty devices and key-operated switches for public area lighting (corridors, etc.), plastic instead of glass in fixtures, and vandalproof equipment wherever possible. All panels *must* be locked and should be located in locked closets.
6. The *NEC* requires sufficient branch circuitry to provide a minimum of 3 V-A/ft^2 (32.3 V-A/m^2) for general lighting in schools (refer to



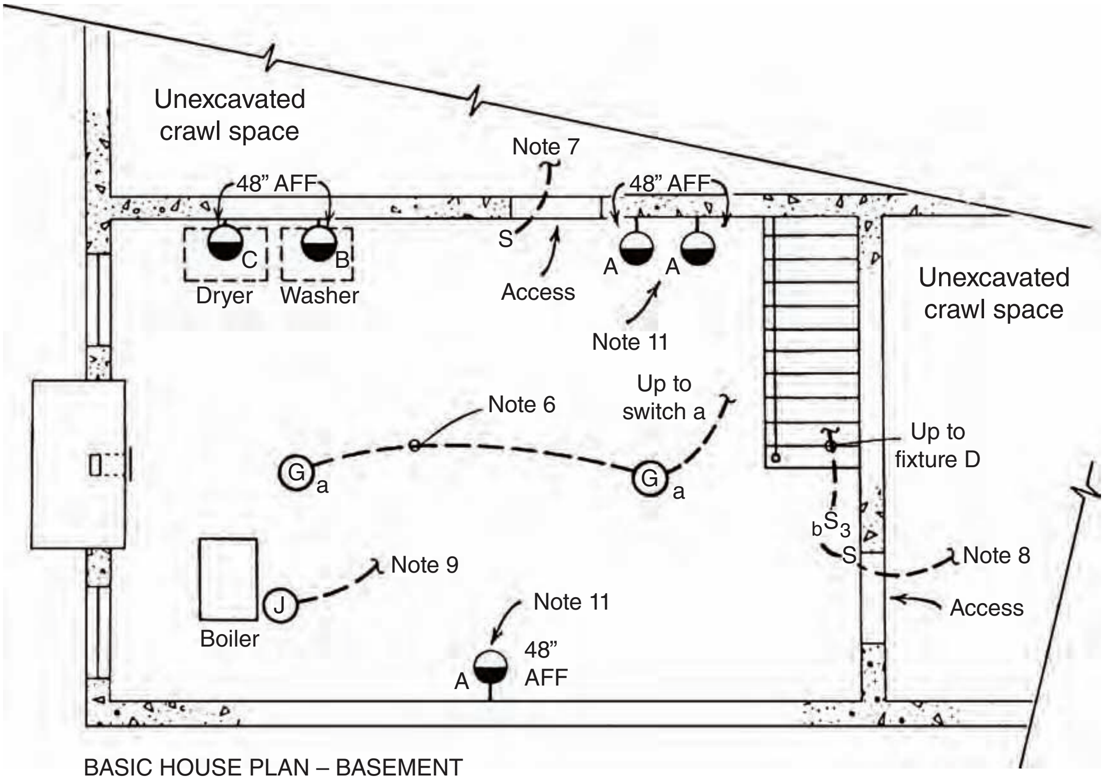
Fixture Schedule: see Fig. 29.20 c
Symbol List: see Fig. 29.20 d
Circuited Plan: see Fig. 29.20 e, f
Plan, Schedule: see Fig. 29.20 g

Notes:

1. Switch and outlet for exhaust fan. Switch wall mtd. above counter-blacksplash. Outlet with blank cover mounted adjacent to fan wall opening. Separate switch may be omitted if fan is supplied with integral switch.
2. Dishwasher receptacle wall mtd. behind unit, 6" AFF.
3. Range and oven outlet boxes wall mtd., 36" AFF. Flexible connection to units.
4. Receptacles at countertop locations to be wall mounted 2" above backsplash.
5. Max. ht. of top c/b to be 78" AFF.
6. Wiring shown as run exposed indicates absence of finished ceiling in basement level. All BX to be run through framing members. Attachment below ceiling joists not permitted.
7. Connect to two type G fixtures ceiling mounted at ⅓ point of crawl space.
8. Connect to one type G fixture at center of crawl space.
9. Connect to shutdown switch at top of stairs. Boiler control wiring by others. See Note 10.
10. Boiler wiring safety disconnect. Provide RED wall plate, clearly marked "BOILER ON–OFF."
11. Equipped with self-closing gasket WP cover.

(*a*)

Fig. 29.20 *Electrical plan of a small house. (a) Layout of lighting and electrical devices for the main floor. (b) Layout of lighting and electrical devices for the basement. (c) Lighting fixture schedule. (d) Symbols and abbreviations. (e) Circuited plan, main floor of house. (f) Circuited plan, basement. (g) Panel schedule for the house.*



BASIC HOUSE PLAN – BASEMENT
ELECTRIC PLAN; H.W. HEATING
EQUIPMENT AND DEVICE LAYOUT

(*b*)

LIGHTING FIXTURE SCHEDULE			
TYPE	DESCRIPTION	MANUFACTURER	REMARKS
A	48" L X 12" W X 4" DEEP NOMINAL, 2 LAMP/FLUORES–CENT, WRAPAROUND ACRYLIC LENS, 40 W (NOM.) T8 LAMPS. SURFACE MTD.	BRITE–LITE CO. CAT. #2/40/KFF OR EQUAL	4" DEPTH MAXIMUM
B	24" L, 1 LAMP 20W FLUOR. FIXTURE, WRAPAROUND WHITE DIFFUSER, MOUNT ABOVE MEDICINE CABINET.	BRITE–LITE CO. CAT. #1/20/BFF OR EQUAL	MAX. MTG. HT. 78" TO ℄.
C	ADJUSTABLE HEIGHT PENDANT INCANDESCENT, 3–75W MAX., BUILT–IN 3–POSITION SWITCH.	HOMELAMP CO. CAT. #3/75/DRP OR EQUAL	———
D	10" D. DRUM–TYPE FIXTURE, WHITE GLASS DIFFUSER, CENTER LOCK–UP, 2–60W INCAND. MAX., SURF. MTD.	BRITELITE CO. CAT. #2/60/HF OR EQUAL	6" MAX. DEPTH.
F	12" D. DRUM FIXTURE, CONCEALED HINGE ON OPAL GLASS DIFFUSER FOR RELAMPING WITHOUT GLASS REMOVAL, 2–75W INCAND. MAX. SURFACE MTD.	DENMARK LIGHTING SPECIAL UNIT #374821	NO SUBSTITUTION WILL BE ACCEPTED.
G	PORCELAIN LAMPHOLDER, PULL CHAIN WITH WIRE GUARD, 100W. INCAND. SURF. MTD.	———	———
H	SAME AS TYPE G, EXCEPT W/O GUARD.	———	———
K	DECORATIVE OUTDOOR LANTERN, MAX. 150W INCAND., WALL MTD. 84" AFF TO ℄.	TO BE CHOSEN BY OWNER	———
L	UTILITY OUTDOOR LIGHT, ANODIZED ALUMINUM BODY AND CYLINDRICAL OPAL GLASS DIFFUSER. 1–100W INCAND. MAX. 84" AFF TO ℄.	UTIL–LITE CO. CAT. #1/100/BP OR EQUAL	IF VANDALISM IS OF CONCERN, SUBST. PLASTIC DIFFUSER.
IR	RECESSED FIXTURE WITH 150 W INFRARED HEAT LAMP	HEAT-LIGHT CO.	———

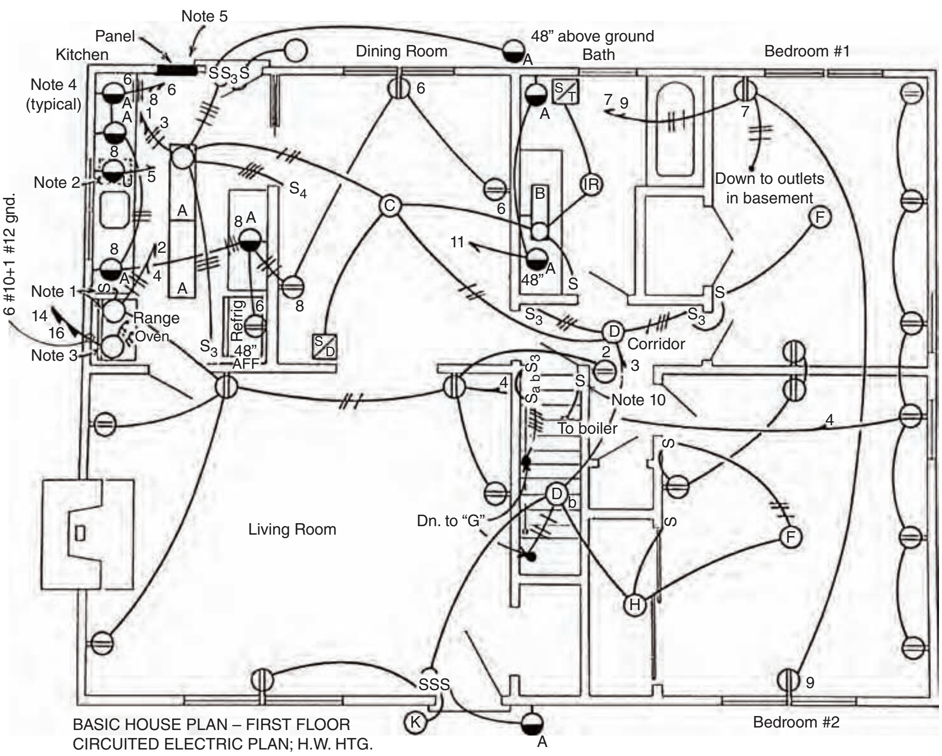
(*c*)

Fig. 29.20 *(Continued)*

SYMBOLS AND ABBREVIATIONS

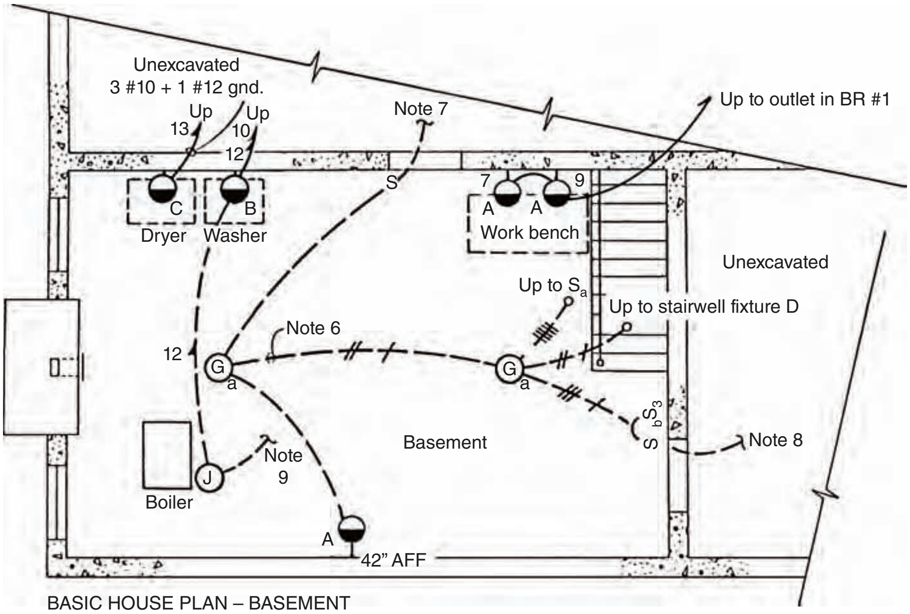
	BX CABLES RUN CONCEALED; TICS INDICATE NUMBER OF CONDUCTORS EXCLUDING GROUND WIRES. 2 #12 + BARE GROUND, UON
	SAME AS ABOVE EXCEPT RUN EXPOSED
	WIRING RUN TURNING DOWN; WIRING TURNING UP
1 3	HOME RUN TO PANEL; ARROWS AND NUMERALS IDENTIFY CIRCUITS; TICS INDICATE WIRING – AS NOTED ABOVE
	OUTLET BOX AND FINAL CONNECTION TO EQUIPMENT WITH FLEXIBLE CONDUIT (OR BX.)
D a	CLG. OUTLET WITH INCANDESCENT LTG. FIXTURE D, SWITCH CONTROL – ‘a’
H	WALL OUTLET W/INCAND. FIXT. ‘H’ , M.HT. SHOWN
A	CLG. OUTLET W/FLUOR. FIXT. ‘A’
B	WALL OUTLET W/FLUOR. FIXT. ‘B’ , M.HT. SHOWN
J	JUNCTION BOX
	DUPLEX CONVENIENCE RECEPTACLE, 20 A, 2P, 3W, 125V, GROUNDING, WALL MTD., VERTICAL, ℄ 12” AFF NEMA 5–20 R
A	DUPLEX CONVENIENCE RECEPTACLES, 15A, 2P, 3W, 125V, GROUNDING. W/INTEGRAL GFCI
B	SINGLE RECEPTACLE, 20 A, 2 P, 3 W, GND’G., NEMA 5–20 R
C	SINGLE RECEPTACLE, 30 A, 125/250 V, 3 POLE–4 WIRE GROUNDING NEMA 14–30 R; SUPPLIED WITH MATCHING CAP
S_a	SINGLE POLE SWITCH, 15 A, 125 V, ℄ 50” AFF, UON, CONTROLLING OUTLET (S) ‘a’
$_aS_3$	SWITCH 3 WAY, 15 A, 125 V, ℄ 50” AFF, UON, CONTROLLING OUTLETS ‘a’
S/T	MANUAL TIMER SWITCH, 1 SET 15 AMP N.O. CONTACTS
S/D	OUTLET BOX MTD. SWITCH AND DIMMER, INCAND. LOAD ONLY, 600 W MAXIMUM, ℄ 50” AFF
	FLUSH MTD. PANELBOARD
AFF	ABOVE FINISHED FLOOR
MH	MOUNTING HEIGHT
T	THERMOSTAT
UON	UNLESS OTHERWISE NOTED
GFCI	GROUND-FAULT CIRCUIT INTERRUPTER
WP	WEATHERPROOF
NO	NORMALLY OPEN

(*d*)



(*e*)

Fig. 29.20 *(Continued)*



BASIC HOUSE PLAN – BASEMENT
CIRCUITED ELECTRIC PLAN,
H.W. HTG.

(*f*)

Panel schedule									
Circ. no.	Description	LOAD V-A.	Circuit breakers			Load V-A.	Description	Circ. no.
1	LTG – {Kit. Dr., Br. #1, Hall, Outside, bath + ⊕	1045 1 R	20	1 2	20	30 6 R	Outlets – LR. & corridor + Exh. fan	2
3	LTG – {Outside Lr., Stair, Br. #2, Bsmt. + 6 ⊕	935 6 R	20	A 3 4	20	6 R	Outlets – BR. 1 & 2	4
5	Dishwasher	1500	20	5 6	20	1500	Outlets – Kit., Dr.	6
7	Outlets – BR 1, Bsmt	2 R	20	7 8	20	1500	Outlets – Kit., Dr.	8
9	Outlets – Bsmt., BR 2	2 R	20	9 10	20	1500	Laundry outlet – Bsmt.	10
11	Bathroom outlets	2 R	20	11 12	20	1300	Boiler	12
13	Spare	—	20	13 14	30 A 2 P	6Kw	Range	14
15	Spare	—	20	15 16				
17	Clothes dryer	5Kw	30 A 2 P	17 18 19 20	30 A 2 P	4800w	Oven	16
	Space for 2 – 1P or 1 – 2 pole			21 22 23 24			Space for 1 – 2P or 2– 1 pole	
	Load total – phase A						Load total, phase B	

Panel Data
Mains, GND. BUS: 150 A MNS., 60 A GND. BUS
Mains C/B 150/100
Branch C/B INT. CAP. AMP. 10,000
Mounting – recess
Remarks: Front suitable for painting

Voltage 120/208
1 PH, 3 wire

(*g*)

Fig. 29.20 *(Continued)*

NEC Article 220). Unlike the value for residential occupancy, this figure does *not* include receptacles. Receptacles are calculated separately at 180 V-A each for ordinary convenience outlets.

(b) Office Space

1. In small office spaces (less than 400 ft^2 [37 m^2]), provide either one convenience outlet for every 40 ft^2 (3.7 m^2) or one outlet for every 10 linear ft (3 m) of wall space, whichever is greater. In larger office spaces, provide one outlet for every 100 to 125 ft^2 (9.3 to 11.6 m^2) beyond the initial 400 ft^2 (37 m^2). These outlets are intended for miscellaneous electrical devices, in addition to anticipating the constantly increasing number of data system accessories. In addition, provide at *every* desk (on an adjacent wall, in a "power pole," or in the floor) at least one duplex 20-A receptacle for a computer. These receptacles should be circuited at no more than six to a 20-A branch circuit, and fewer if the specific equipment to be powered so dictates. Figure 29.21 shows one possible circuiting arrangement for the room layouts shown in Fig. 29.12. Although other arrangements are possible, the net result is the same (see also Fig. 29.22).
2. Corridors should have a 20-A, 120-V outlet every 50 ft (15 m) to provide power for cleaning and waxing machines.
3. As with all nonresidential buildings, convenience receptacles are figured at 180 V-A each.
4. Only specification grade equipment should be used.

(c) Industrial Spaces

These areas are so specialized that no meaningful general guidelines can be given.

(d) Stores

In stores, good practice requires at least one convenience outlet receptacle for every 300 ft^2 (28 m^2) in addition to outlets required for loads such as lamps, show windows, and demonstration appliances.

29.14 LOAD TABULATION

While the designer is circuiting loads, he or she draws up a panel schedule that lists the circuit numbers, load descriptions, wattage (actually, volt-amperes), and the current rating and number of poles of the circuit-protective device feeding each circuit. Spare circuits are included to the extent that the designer considers them necessary and consistent with design intent (including budget), but normally no less than 20% of the number of active circuits. Finally, spaces are left for future circuit breakers in approximately the same quantity as the

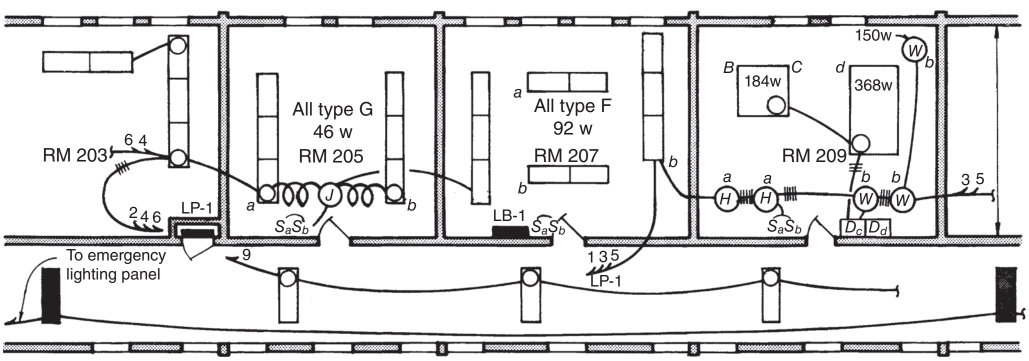


Fig. 29.21 *Alternative methods of circuiting are shown in different rooms. Room 205 shows the actual junction box location, with flexible connections to the box at each fixture. Room 207 shows circuit numbers and switch designations only; the placement of junction boxes is understood, and conduit runs are omitted for clarity and because they usually are not representative of the actual field installation. Room 209 shows an outlet box at each fixture, with schematic conduit connections. All of these methods are in common use.*

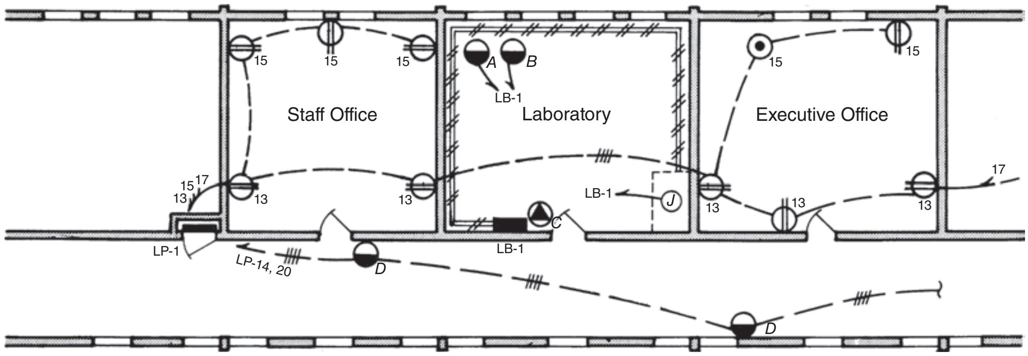


Fig. 29.22 Typical receptacle circuiting of several rooms in an office–laboratory building. Lighting (see Fig. 29.21) and power (receptacles) are shown on separate plans to avoid crowding. See Fig. 29.15 for symbols and Fig. 29.12 for notes. Lighting in offices is recessed; lighting in labs is surface-mounted for flexibility. Note the double circuiting of the type-D receptacles.

number of spare circuits, but always so as to round off the total number of circuits.

Panelboards are normally manufactured with an even number of poles. Thus, if a panel had, with spares, 21 poles, the designer would ask for (at least) three spaces, to give a 24-circuit box. A typical panel schedule is shown in Fig. 29.23, which serves the laboratory of Figs. 29.21 and 29.22.

In calculating panel loads, the following rules apply:

1. Each specific appliance, device, lighting fixture, or other load is taken at its nameplate rating, except certain kitchen and laundry appliances for which the *NEC* allows application of a demand factor (see *NEC* Article 220).
2. Each convenience outlet, in other than residential spaces, is counted as 1.5 A (180 V-A).
3. Loads for special areas and devices such as show window lighting, heavy-duty lampholders, and multioutlet assemblies are taken at the figures given in *NEC* Article 220.
4. Spare circuits are figured at approximately the same load as the average active circuits (1200 to 1500 V-A).
5. Spaces are not counted in the load.
6. Continuous loads such as lighting are calculated at 125% of their actual value. See *NEC* Articles 210-19(A) and 210-20(A), which refer to load calculations for conductor sizing and feeder overcurrent protection, respectively, for combinations of continuous and noncontinuous loads. These calculations apply to panel load calculations as well and are best accomplished by adding 25% to the panelboard load, as shown in Fig. 29.23.

In calculating total panel loads, as shown in Fig. 29.23, no demand factor may be applied except as specifically stated in the *NEC* (see *NEC* Articles 220-40). This is true despite the knowledge that most often the usage will be such that the average load will be lower than the maximum demand (see Section 29.17 for multipanel feeders). If it is known that certain loads will not or cannot be used simultaneously, the load total should reflect only the larger of the two. Thus, heating and cooling loads are *generally* not concurrent. Nor is building night floodlighting concurrent with the business office load, but it may be with general interior lighting. Note in Fig. 29.20*g* that 2-pole loads (208 single-phase) appear in two columns. Similarly, 3-phase loads would appear in three columns. Also, note that the phase loads are *not equal*. It is the responsibility of the designer (or contractor) to circuit the loads so that the phases are as closely balanced in load as possible. If this is not done, one phase will carry considerably more current than the others. Because the panel feeder must be sized for the maximum phase current, this may lead to an oversized feeder and therefore a waste of money.

Once the loads have been tabulated, balanced, and totaled by phase, the maximum current is calculated. A portion of the spare capacity available in the branch circuits is added to the total as the basis for the calculation of the feeder load. This spare capacity, shown in Table 29.5, is between

	ELEC. PANEL-LP-1			
	120/208 V 3φ 4W	LOAD IN WATTS		
No.	LOAD	φA	φB	φC
1	Lighting	1200		
2	Lighting	1200		
3	Lighting		1450	
4	Lighting		1050	
5	Lighting			1100
6	Lighting			1200
7	Lighting	800		
8	Lighting	1100		
9	Lighting		700	
10	Lighting		1050	
11	Lighting			1000
12	Lighting			1200
13	Receptacle 2	900		
14	Receptacle 3	900		
15	Receptacle		900	
16	Receptacle		900	
17	Spare			1200
18	Spare			1200
19	Spare	1200		
20	Receptacle 4		1000	
				1000
21	Spare	1200		
			1200	
22-26	Spaces only			
	25% addition for			
	continuos loads 5	1025	1063	1125
	Phase totals	9525	9313	9025
	Panel total		27863	V-A
	Max φ current		77 amp	
	25% spare capacity	~	20 amp	(Future)
	Max. Phase I		97 amps	

Main breaker 225A 3pole (see text example 17.1, section 17.18)
Trip 100 A
Feeder size 4 #2 THW in 1 1/4"C.

NOTES:
1. All C/B 1P; 50A frame, 20A trip except ccts 20 and 21, which are 2P, 50AF/20AT.
2. 5 receptacles @ 1.5A each.
3. Corridor receptacle; 120 V section.
4. Corridor receptacle; 208 V section.

Fig. 29.23 *Schedule for lighting panel LP-1 (see Fig. 29.22).*

25% and 50%. The exact amount to be initially added in feeder sizing is developed in the ensuing discussion.

29.15 SPARE CAPACITY

Load calculations for residential occupancies and other spaces are detailed in *NEC* Article 220, and examples are given in Chapter 2 of the *NEC*. Because these calculations are specialized (but routine) and are covered there in detail, they are not repeated here. Code requirements, it must be remembered, are minimum; a design solution to meet a client's needs often exceeds these basic requirements.

Once the panel load totals have been determined as detailed previously, the next step is to size the conductors feeding the panel. To do this, an examination of the spare capacity of the panel and of the feeders is necessary in order that the system design be consistent, giving equal capacity for future growth in all of its components. Considering the panel circuitry first, let us examine the effect of load expansion, including spares and spaces (Table 29.8).

As noted in Section 29.11, spare capacity is built into the branch circuitry *and* into the panels. Most often, expansion is accomplished by additional loading on some circuits and by adding new circuits via spare circuit breakers in the panel. Table 29.8 gives the *ultimate* capacity of the panel—that is, fully loaded circuits and fully utilized spares and spaces. Because this ultimate capacity is rarely achieved, panel feeders need only be sized for initial loads as detailed in Section 29.14, and provision made for rewiring to meet anticipated expansion by one of the techniques listed in Section 29.16.

These results can be summarized as follows: For panels in buildings expecting limited expansion, for which branch circuits are loaded to 80% of capacity (25% *branch circuit* expansion; see Table 29.5, note *e*), the ultimate panel load without new conduit work (i.e., merely by filling out circuits) is 1.5 L, or 50% beyond the initial load. By adding breakers in the spaces, this load can be expanded to 75% beyond the initial load. The corresponding figures for panels that are lightly loaded (66% capacity, i.e., 50% branch circuit expansion, as in Table 29.5, note *f*), in anticipation of considerable load growth, are 80% to 110%, respectively. These results are summarized in Table 29.8.

29.16 FEEDER CAPACITY

To achieve economy, the panel feeder must accommodate the initial load plus some portion of the future load. Spare capacity in feeders (to accommodate a considerable portion of the panel spare

TABLE 29.8 Panel Initial and Expanded Loads[a]

	Panels in Facilities Expecting Limited Expansion; Circuits Initially Loaded to Give 25% Expandability (See Table 29.5)	Panels in Facilities Expecting Extensive Expansion; Circuits Initially Loaded to Give 50% Expandability (See Table 29.5)
Initial load	100%	100%
Initial plus spares	120%	120%
Load after all circuits including spares are loaded to maximum allowable	150%	180%
Load after utilizing 20% spaces also	175%	210%

[a]For development of these values, see McGuinness et al. (1980), pp. 690–691.

capacity, as shown in Table 29.8) is provided by one or more of the following procedures:

1. Provide feeder (and conduit) capacity initially to handle the entire eventual load. This method is the most expensive, requiring an initial outlay for (potentially) no return, and is rarely used.
2. Provide feeder capacity for the initial load plus spare capacity, with properly sized conduit. Conduit is sized for type THW or RHW without covering. This method yields limited spare capacity.
3. Provide feeder capacity for the initial load plus spare capacity, with conduit oversized by one size. Size conduit for type THW wire, which is very widely used because of its attractive price and excellent electrical properties. Some additional costs are entailed here.

   If the initial wiring is done with type TW wire, the effect is approximately the same as that of oversizing the conduit by one size and wiring initially with THW wire. This is the result of the lower ampacity rating of TW compared to THW, resulting in a larger conduit size for the same initial ampacity. Exact figures for each can be worked out with the help of Tables 28.2A, and 28.2B, and conduit capacity in Table 29.9, or by using the tables in *NEC* Article 310 and Chapter 2.
4. Provide feeder capacity for the initial load plus spare capacity and oversize conduit by *two* sizes. This yields most of the capacity necessary in facilities anticipating large expansion.
5. Provide for the initial load plus spare capacity, and install an empty conduit for future use. This method is expensive because of the high conduit cost and is advisable only infrequently.

In approaches 2, 3, and 4, the future capacity beyond that initially supplied is handled by the use of larger-gauge wire in the existing conduit. To examine exactly what these alternatives provide in spare capacity, Table 29.10 tabulates the maximum ampacity of various sizes of conduits and the future capacity obtainable. Table 29.9 is taken directly from the *NEC*. Note from Table 29.10 that simply by rewiring, up to 30% additional capacity can be obtained, whereas if the conduit had been oversized, the additional capacity would be 35% to 146%.

Answering the question of how large to make the feeder for a given panel load requires balancing the future panel load, the initial cost of feeder, and the future capacity of existing conduit. It is best to avoid the installation of empty conduits because this is expensive. Rewiring, however, is relatively inexpensive, and oversizing conduit is the method of choice if rapid expansion is anticipated.

Referring to Table 29.10, note that normal design uses THW cable. Design with T or TW is, in effect, a first step in oversizing conduit and is generally not economical. The second step is a deliberate oversizing of conduit that results in much increased conduit ampacity, as reflected by the figures in the table. Using these values in practice requires that the designer juggle cable and conduit costs against anticipated load growth to arrive at the most economical long-term solution. Applying these numbers to concepts previously developed, suggests:

1. Buildings designed for 25% branch circuit expansion (see Table 29.5) have a panel capacity of 1.75 times the load (Table 29.8). If it is desired to design the panel feeder to carry the full expansion possible, then calculate the feeder on the basis of panel load plus 20% spares and oversize the feeder by 20%. This gives a feeder capacity of

$$1.20 \times 1.20 = 1.44 \times \text{initial load}$$

TABLE 29.9 Maximum Number of Conductors in Trade Sizes of Rigid Metal Conduit

		Conduit Trade Size (in.)									
Type Letters	**Conductor Size AWG, kcmil**	**½**	**¾**	**1**	**1¼**	**1½**	**2**	**2½**	**3**	**3½**	**4**
TW, THW, RHW, RHH (without outer covering), and THHW	6	1	3	5	8	11	18				
	4	1	1	3	6	8	14	20			
	2	1	1	2	4	6	10	14			
	1	1	1	1	3	4	7	10			
	0		1	1	2	3	6	8	13		
	00		1	1	2	3	5	7	11		
	000		1	1	1	2	4	6	9	13	
	0000			1	1	1	3	5	8	10	
	250			1	1	1	3	4	6	8	11
	300			1	1	1	2	3	5	7	9
	350				1	1	1	3	5	6	8
	400				1	1	1	3	4	6	7
	500				1	1	1	2	3	5	6
	600				1	1	1	1	3	4	5
THHN	6	2	4	7	12	16	27				
	4	1	2	4	7	10	16	24			
	2	1	1	3	5	7	12	17	26		
	1	1	1	1	4	5	9	12	19	26	
XHHW (4–500 kcmil)	0	1	1	1	3	4	7	10	16		
	00		1	1	2	3	6	9	13		
	000		1	1	1	3	5	7	11	15	
	0000		1	1	1	2	4	6	9	12	16
	250			1	1	1	3	5	7	10	13
	300			1	1	1	3	4	6	9	11
	350			1	1	1	2	3	6	7	10
	400			1	1	1	2	3	5	7	9
	500				1	1	1	2	4	5	7
	600				1	1	1	1	3	4	

Source: Extracted from the *National Electrical Code*.

Table 29.10 indicates that rewiring adds another 20% on average. This gives

$$1.20 \times 1.44 = 1.73 \times \text{initial load}$$

which corresponds very closely to the 1.75 desired.

2. For a building with 50% branch circuit expansion, utilizing the full panel space capacity creates an ultimate panel capacity of 2.1 times the initial load (see Table 29.8). This is accomplished as follows: Oversize the feeder by 15% and oversize the conduit by one size. The latter step gives an average expansion of 65%. Therefore,

$$\text{feeder capacity} = 1.15 \times 1.20 \times 1.65 = 2.3$$

which is approximately the desired figure.

TABLE 29.10 Maximum Wire and Ampacity of a Conduit, and Ampacity Gain on Rewiring

	Initial Installation THW Cable		*Rewiring with XHHW*				
			Using Original Conduit			Capacity Increase Having Oversized Conduit	
Initial Conduit Size (in.)	**Max.[a] Wire AWG/ kcmil**	**Max. Amperes**	**Maximum Wire**	**Maximum Amperes**	**Capacity Increase**	**One Size**	**Two Sizes**
1½	1	130	1/0	170	30%	100%	146%
2	3/0	200	4/0	260	30%	60%	115%
2½	250	255	300	320	25%	69%	100%
3	400	335	500	430	28%	35%	81%
3½	600	420	600	475	13%	64%	—

[a]Assuming four single conductors in conduit: 3-phase conductors plus neutral.

If, as in the case of laboratories, more than 100% expansion is anticipated (see Table 29.1), conduit should be oversized by two sizes and initial wiring oversized by approximately 25%. Feeders thus arranged will handle the new panels required to meet the anticipated expansion.

Two factors should be carefully noted here. First, the smaller conduits offer the largest expandability, although, in dollars per amperes, they are more expensive. Second, in order to take advantage of spaces in a panel, conduit stubs should be taken from the panel and extended into suspended ceilings (or another procedure used to make the panel circuitry easily accessible in the future).

29.17 PANEL FEEDER LOAD CALCULATION

EXAMPLE 29.1 Refer to Fig. 29.23. The panel is for a laboratory/office area. Because substantial expansion is anticipated, circuitry follows the bottom section of Table 29.5. The ultimate panel load would be 26 circuits at 1920 V-A = 50 kVA = 138 A. Thus, the initial feeder is sized for 115 A (4 #2 THW, 1¼ in. C), but rewiring with XHHW will allow as much as 150 A in the same conduit. A 225-A frame circuit breaker is chosen initially because eventually the trip will be raised to 150 A. ■

The *NEC* in Article 220 specifies minimum volt-amperes per unit area (V-A/ft^2 [V-A/m^2]) values for various occupancies, for lighting, and for miscellaneous power loads. Proper design procedure therefore requires that after detailed design of an area, the actual loading should be compared to these minima, and the larger of the figures, concerning the number of circuits and feeder load, should be used. An example will help to make this clear.

EXAMPLE 29.2 Assume a single floor of an office building of 100 × 200 ft (30.5 x 61 m). Assume also that 15% of the area is corridor and storage, equally divided between the two. Calculate the load and feeder size. Assume a good-grade speculative construction venture.

SOLUTION

Office space	= 85% of 20,000 ft^2 (1860 m^2)
	= 17,000 ft^2 (1581 m^2)
Corridor and storage	= 15% of 20,000 ft^2 (1860 m^2)
	= 3000 ft^2 (279 m^2)

The *NEC* specifies a minimum of 3½ V-A/ft^2 (37.7 V-A/m^2) for lighting and 1 V-A/ft^2 (10.8 V-A/m^2) for miscellaneous receptacles in office space. It further specifies ½ V-A/ft^2 (5.4 V-A/m^2) minimum for corridors and ¼ V-A/ft^2 (2.7 V-A/m^2) for storage. Therefore:

LIGHTING		
Office load:	17,000 × 3½	= 59.5 kVA
	(1581 × 37.7)	= 59.5 kVA
Corridor:	1500 × ½	= 0.74 kVA
	(139 × 5.4)	= 0.74 kVA
Storage:	1500 × ¼	= 0.38 kVA
	(139 × 2.7)	= 0.38 kVA
Minimum lighting load		= 60.6 kVA
RECEPTACLES		

$$17{,}000 \times 1 \text{ V-A/ft}^2 = 17 \text{ kVA}$$
$$(1581 \times 10.8 = 17 \text{ kVA})$$

These values would then be compared to the actual design loads. Receptacles are counted at 180 V-A each, as noted in Section 29.14, item 2. If the code minima exceed the design load (as they well may if lighting is carefully designed), panels must be equipped with sufficient additional circuits to make up the difference. The number of such circuits is up to the designer, because circuit loading is not specified.

For instance, suppose that the lighting design was accomplished at 2 V-A/ft^2 (21.5 V-A/m^2). Panel circuits would have to be provided for the additional 1½ V-A/ft^2 (16.2 V-A/m^2) as follows:

$$17{,}000 \text{ ft}^2 \times 1.5 \text{ V-A/ft}^2 = 25.5 \text{ kVA}$$
$$(1581 \text{ m}^2 \times 16.2 = 25.5 \text{ kVA})$$

Assuming a 30% to 50% future load expansion, we would circuit the lighting loads at approximately 1300 V-A per circuit (see Table 29.5). Therefore, we would provide

$$\frac{25{,}500 \text{ V-A}}{1300 \text{ V-A}} = 20 \text{ additional circuits}$$

With respect to the minimum feeder load, the *NEC* specifies that it be increased by 25% if loads are continuous (3 or more hours). This requirement allows for breakers to heat up in panels while carrying a continuous load and is waived for circuit breakers that are ambient compensated—that is, are rated to carry 100% load. Because we have established 80% of the breaker rating as the maximum load (see Table 29.5), we have already accounted for this factor in circuitry but must utilize it in the feeder calculation. Assuming that the code minima are the design loads, then, for feeder calculation:

$$\text{Lighting load} = 60.6\,\text{kVA} \times 125\% = 75.75\,\text{kVA}$$
$$\text{Receptacle load, as given} = 17.0\,\text{kVA}$$
$$\text{Minimum feeder load} = 92.75\,\text{kVA}$$
$$25\%\ \text{future load} = 23.2\,\text{kVA}$$
$$\text{Design feeder load} = 116\,\text{kVA}$$

Because this load would be divided among several panels, the building electrical design might be such that the panels are not all fed by one feeder (see Fig. 29.24). Assuming they are, however, the feeder would be calculated in terms of 3-phase current thus:

$$I = \frac{\text{kVA}}{0.360} = \frac{116}{0.360} = 322\ \text{A}$$

Using THW cable, a minimum of 400 MCM would be required. Conduit would be a minimum of 3 in. but might be increased to 3½ or 4 in., according to the considerations of spare capacity discussed in the previous section. ■

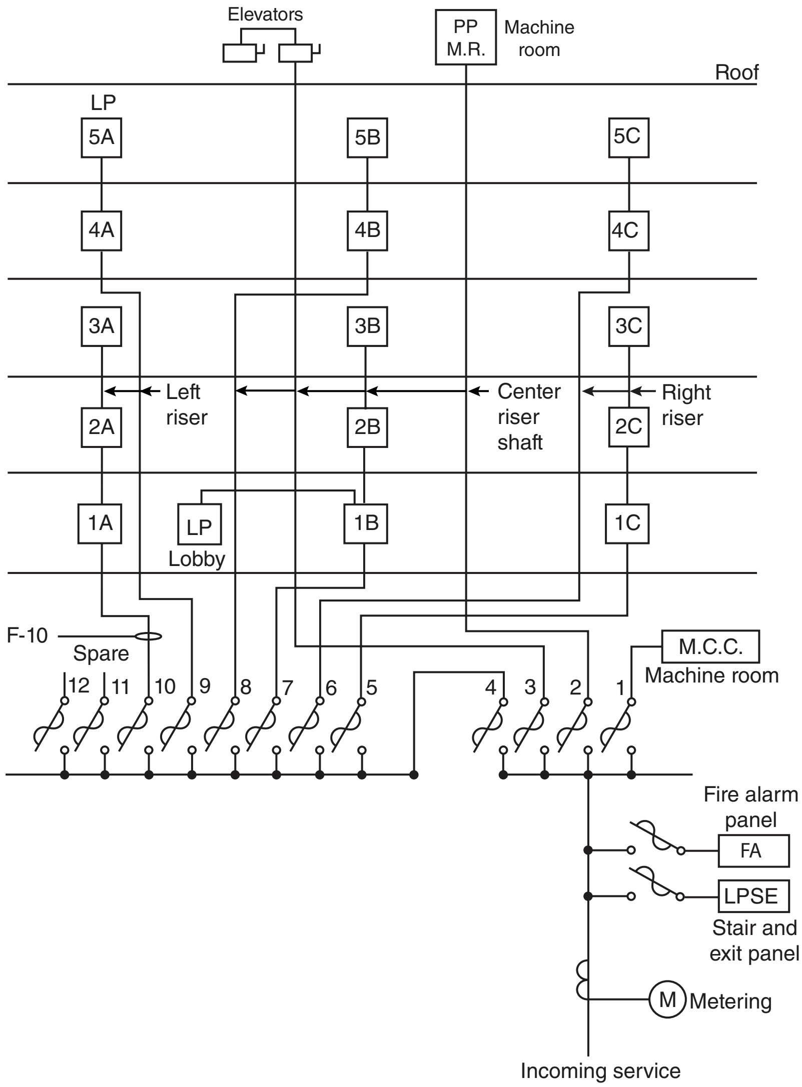


Fig. 29.24 *Typical power riser diagram. Ordinarily, the main switchboard would be shown as a large rectangle with the feeders emanating from it, and a switchboard schedule would detail the contents. Here, because of the unusual bus arrangement, the main switchboard appears as it would on a single-line diagram.*

TABLE 29.11 Current and Volt-Ampere Relationships

120-V Single-Phase	120/240-V 3-Wire	120/208-V Single-Phase, 3-Wire	120/208-V 3-Phase	277/480-V 3-Phase	277-V Single-Phase
$I = (V–A)/120$	$I = (V–A)/240$	$I = (V–A)/208$	$I = (V–A)/360$	$I = (V–A)/830$	$I = (V–A)/277$

Table 29.11 lists the relevant relations that will assist in computing currents. A note of caution is required regarding the use of computer programs to perform the previous calculations. It should be very clear that considerations of economy and anticipated expansion must be considered in designing a feeder system. Most software will not make such necessary comparisons and calculations unless specifically directed, and this frequently requires a multistage calculation. Most programs are arranged to select feeders on the basis of current loads, plus a specified spare capacity, without regard to expansion or economic considerations. It is important to understand the methods used by any particular computer program in order to apply its output intelligently.

29.18 HARMONIC CURRENTS

Large harmonic currents have been the cause of considerable difficulty in modern electrical installations. Without going into detail on this highly technical subject, a brief description of the problem and its causes is given here.

Conventional electrical loads such as lighting, resistive devices (heaters), motors, and the like are linear (i.e., the load impedance remains essentially constant, regardless of instantaneous voltage). This is not the case with most electronic equipment. Computers, modems, printers, electronic lighting ballasts, variable-speed motor drives, and solid-state equipment of all types are essentially nonlinear loads. As such, they produce harmonic currents, of which the odd-order ones are additive in the power system neutral conductor. The most troublesome of these are the third harmonic and its odd multiples (9th, 15th, 21st, . . .). These currents can become so large in a modern computerized office (especially with electronic ballasts) that instead of the neutral conductors carrying the unbalanced current in a 3-phase system (zero in a balanced system), they actually carry *more* current than the phase wires.

Other serious negative effects of harmonic currents are:

- Deterioration of electronic equipment performance; continuous or sporadic computer malfunctions
- Overheating of the neutral—possibly causing neutral burnout and resulting in equipment being subjected to severe voltage variations
- Overheating and premature failure of transformers—even when the transformer nameplate rating seems adequate
- Overheating of motors because of operation with a distorted voltage waveform
- Nuisance tripping of circuit breakers and adjustable-speed drives
- Telephone interference
- Capacitor fuse blowing.

The problem of destructive harmonic currents becomes progressively more severe as the amount of electronic equipment in use increases (as it does continuously).

Today, at least half of the electric load in a modern office-type facility is composed of nonlinear, harmonic-producing equipment. It follows that all such facilities, both existing and under design, must take necessary corrective measures. In the past, these measures consisted of oversizing equipment to avoid overload burnout; adding passive harmonic filters (which act to reduce harmonic content) in the electric distribution system; using isolation transformers at sensitive loads; selecting power sources with low output impedance to minimize voltage distortion; using controls that are relatively insensitive to harmonic distortion; adding meters throughout the system that measure true rms voltage and current rather than the average values shown by conventional meters; and other expensive (and essentially passive) power line conditioning (see Sections 27.35 and 27.36). In view of the increasing severity of the problem, computer-controlled variable power-conditioning equipment (called *active* line conditioning) has become available. Such power-conditioning equipment operates in a fashion similar to that described for active noise cancellation in Section 24.28. The conditioner instantaneously and continuously analyzes the harmonic content of the line voltage and injects an equal but exactly out-of-phase voltage to cancel the harmonics and produce a pure sinusoidal voltage supply. The harmonic currents that are required by nonlinear loads are supplied by a digital signal generator. Other techniques are also used; their description is beyond the scope of this book.

In any retrofit work, the electrical designer must obtain a detailed electrical system analysis for the existing system, performed by engineers experienced in the field of power quality. Many existing systems carry as much as 70% to 80% harmonic current and constitute a major system failure waiting to happen. A proper power quality study, performed with such instruments as true rms meters, harmonic analyzers, frequency selective voltmeters, and spectrum analyzers, will yield a true picture of an existing system and permit the electrical rehab work to be engineered with harmonic limitations as one of the important design parameters.

29.19 RISER DIAGRAMS

When all devices are circuited and panels are located and scheduled, a riser diagram can be prepared. A typical diagram, shown in Fig. 27.2, represents a block version of a single-line diagram except that, as the name implies, vertical relationships are shown. All panels, feeders, switches, switchboards, and major components are shown, up to, but not including, branch circuiting. This diagram is essentially a vertical section taken through a building electrical system.

EXAMPLE 29.3 Feeder F10 of Fig. 29.24 serves lighting panels 1A, 2A, and 3A. Calculate the required feeder size, considering loads, future expansion, and voltage drop.

SOLUTION

The connected loads on these panels have been computed in accordance with the previous considerations and are:

LP-1A—110 A
LP-2A—125 A
LP-3A—100 A
335 A

These values include connected load, spares, and a 25% future capacity factor (the *NEC* requires that feeders be sized minimally for loads calculated by using the given *NEC* unit area loads plus any demand factors listed; see Article 220). If actual panel circuit loads are larger than the *NEC* minima, then the actual loads are used in feeder calculations, and any reasonable demand may be used, provided that at no time do the totals drop below the minima specified in the *NEC*. Therefore, diversity factors may be applied between panel loads in a judicious manner.

In office building work, typical diversity factors are as follows:

Lighting Panels Fed from a Single Feeder	Diversity Factor
1 or 2	1.00
3 or 4	1.09
5, 6, or 7	1.18
8, 9, or 10	1.33

Thus, the load on feeder F10, using 100% demand per panel and 1.09 diversity between panels, would be 335 × 1.0/1.09 = 307 A. ■

Methods for handling future expansion were discussed previously. In this case, the feeder, before voltage drop considerations, would be (from Tables 28.2, 28.3, and 29.9) 4-350 MCM THW in 3-in. C. In this case, the values in Table 29.10 can be misleading if not read carefully. A 3-in. conduit will take a maximum of 400 kcmil THW. However, because the initial design is using only 350 kcmil, which also requires a 3-in. conduit, the expansion possible by rewiring with XHHW is

$$\frac{\text{ampacity of 500 kcmil, XHHW in 3-in. C}}{\text{ampacity of 350 kcmil, THW in 3-in. C}}$$

$$= \frac{430\text{ A}}{310\text{ A}}$$

$$= 1.39\text{—i.e., 39\% expansion}$$

This should be sufficient.

The final consideration in sizing a feeder is voltage drop. The *NEC* suggests (does not require) that sizing branch circuit conductors for a maximum of 3% voltage drop to the farthest outlet, and sizing feeders so that the maximum *combined* feeder and branch circuit voltage drop to the

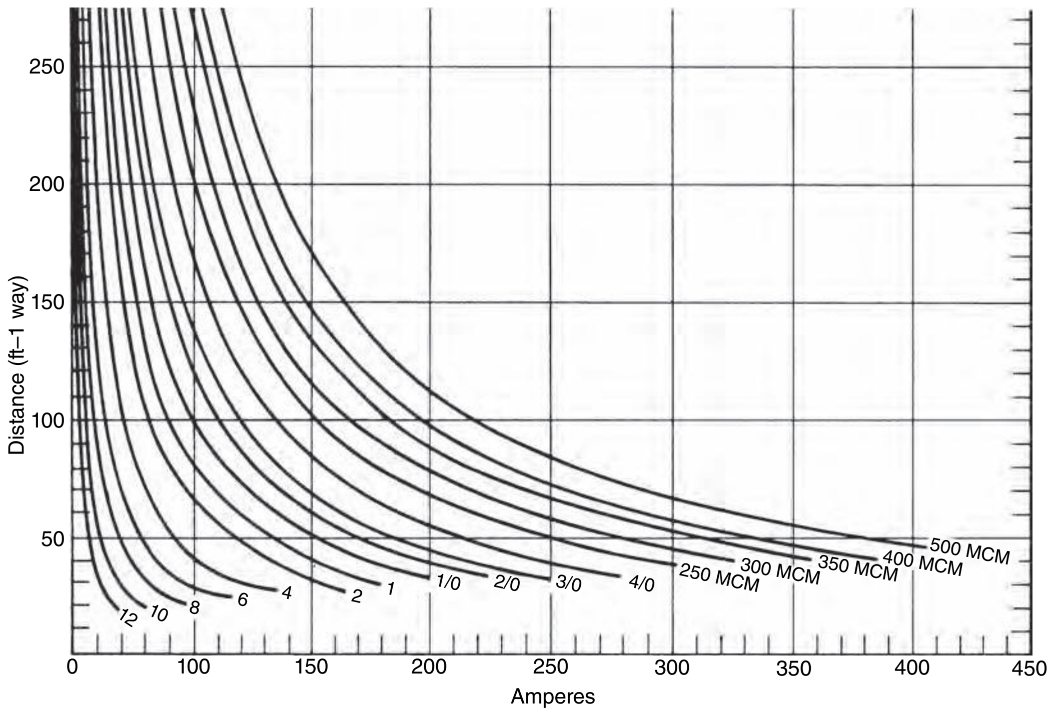


Fig. 29.25 *Curves for determining voltage drop in copper cables. Curves show the maximum one-way circuit length for a 1% voltage drop.*

farthest outlet does not exceed 5%, will give reasonably efficient operation. These figures apply to all types of loads.

It is suggested that it makes economic sense to restrict branch circuit voltage drop to 2% to the farthest outlet while maintaining the overall 5% limitation. This allows a minimum 3% drop in feeders, which are frequently long and, because of size and ampacity inefficiency, relatively more expensive than small branch circuit wiring.

Many tables and curves are published by manufacturers from which voltage drop can be obtained. Such a set of curves is shown in Fig. 29.25, which shows the maximum length of run for a 1% drop. Applying these curves to Example 29.3 and assuming an 80-ft (24 m) run gives the following.

From the curves, 307 A on 350 MCM cable gives a 1% drop in 50 ft (15 m). Therefore, the drop in 80 ft (24 m) will be 1.6%, which is well within our criteria, assuming that branch circuits were limited to a 2% voltage drop.

In summary, then, feeders are sized in accordance with load (actual or based upon unit area, whichever is larger) and voltage drop. Conduit may be oversized to address the potential for substantial future load expansion.

29.20 SERVICE EQUIPMENT AND SWITCHBOARD DESIGN

The main switchboard shown in Fig. 29.24 constitutes a combination of service equipment and feeder switchboard. The service equipment portion of the board comprises the metering and four main switches feeding the risers, motor control center (MCC), rooftop machine room, and elevators. The feeder board comprises switches 5 through 12. Such an arrangement is permissible inasmuch as the *NEC* allows up to six fused switches or circuit breakers to serve as the service disconnect means. This arrangement was chosen in order to separate to the largest extent possible the motor loads (elevators, air-conditioning equipment, basement power, etc.) from the lighting. Such a procedure minimizes lighting fluctuations resulting from motor starting and yields simpler maintenance. Also, the size of the main switch is reduced. This switchboard would be of the metal-clad deadfront type with switches or circuit breakers, as desired.

Other recommendations affecting service equipment are as follows:

- All equipment used for service, including cable, switches, meters, and so on, should be approved for that purpose.
- It is recommended that a minimum of 100-A, 3-wire, 120/240-V service be provided for all individual residences.
- No service switch smaller than 60 A, or circuit breaker frame smaller than 100 A, should be used.
- In multiple-occupancy buildings, tenants must have access to their own disconnect means.
- All building equipment should be connected on the load side of the service equipment, except that service fuses, metering, fire alarm and signal equipment, and equipment serving emergency systems may be connected ahead of the main disconnect (see Fig. 29.24).
- For additional information on electric service, see *NEC* Article 230.

29.21 EMERGENCY SYSTEMS

(a) General Information

Some considerations relevant to power reliability are discussed in Section 29.1(b), and a brief review of the equipment available to supply emergency power is presented in Section 27.39. Emergency lighting equipment is covered in Section 17.31. This section discusses possible emergency power supply arrangements. The choice of arrangement and the size and type of equipment depend largely upon the requirements of local codes, which determine the loads that must be supplied from the emergency system. Although this section uses the term *emergency*, the concepts involved are equally applicable to standby systems. Where differences occur, they are pointed out.

The three classes of electrical power supply systems that are included under the general category of emergency electric supply systems are:

- Emergency Systems: covered by *NEC* Article 700
- Legally Required Standby Systems: covered by *NEC* Article 701
- Optional Standby Systems: covered by *NEC* Article 702

The essential differences among the three classifications involve the purpose, application, and duration of the specific nonnormal power supply. All three types are activated when normal power fails, but only the first two types are legally required when so specified by a governmental agency having jurisdiction. Optional standby systems are, as their name states, optional; they are entirely dependent upon the project requirements established by the facility's owner or operator.

Emergency systems are those essential to human safety. As such, and depending upon the type of facility involved, they may supply power for fire detection, lighting, alarm and communication systems, elevators, fire pumps, and such loads as ventilation, refrigeration, and industrial processes where power interruption would imperil human safety. Generally, emergency systems must pick up the loads automatically within 10 seconds of power interruption. Where the emergency power supply consists of batteries, they must have a full-load capacity of 90 minutes. Where the power supply is an engine–generator set, an on-site fuel supply that will suffice for a minimum of 2 hours of full load is required. The entire wiring system for an emergency power system must be separate and distinct from the normal power system, except where both systems are connected to the same item of equipment.

Legally required standby systems are those required to provide power for essentially the same types of loads as emergency systems, except that their absence does not involve immediate danger to human life. Systems for firefighting, control of health hazards, long-term rescue operations, and industrial hazard prevention would be among the electrical loads served. For these systems, loads must be picked up automatically within 60 seconds of failure of normal power and be maintained for the same minimum periods of time specified for emergency power systems. Wiring may be run in the same enclosures as those used for the normal power system.

Optional standby power systems are intended essentially to minimize economic loss, and therefore can supply any load identified by the building owner. Connection of the selected standby source can be manual or automatic, and the duration of service is entirely at the owner's discretion. No restrictions are placed on the wiring system beyond those applied to the normal electrical wiring system.

(b) NFPA Codes

The *NEC* does not determine whether an emergency system is required; that decision is made by the applicable jurisdictional authorities and is generally a response to the requirements of NFPA 101. Once a determination to provide an emergency system has been made, however, the equipment and installation must comply with the requirements of the *NEC*. Relevant NFPA codes (updated on a regular basis) include:

NFPA 70:	*National Electrical Code*
NFPA 99:	*Standard for Health Care Facilities*
NFPA 101:	*Life Safety Code*
NFPA 110:	*Standard for Emergency and Standby Power Systems*
NFPA 111:	*Standard on Stored Electrical Energy Emergency and Standby Power Systems*

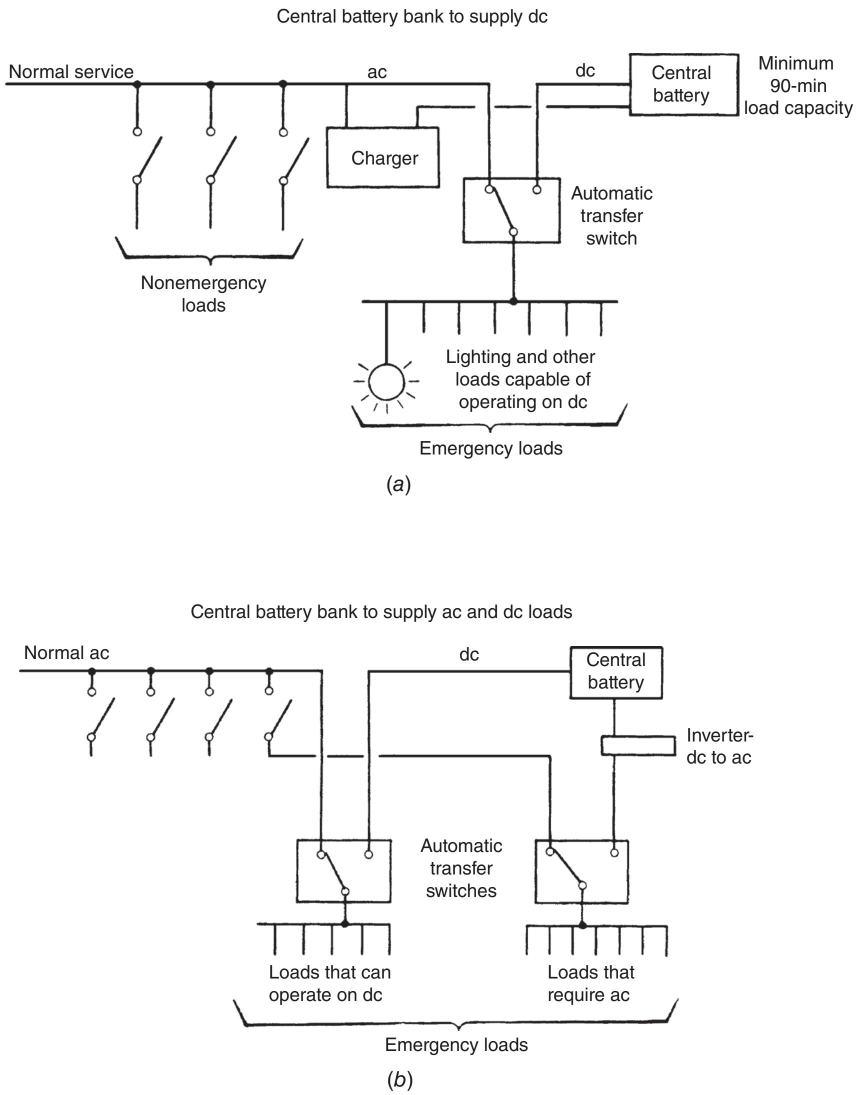


Fig. 29.26 *Use of a central battery for emergency power supply. When all loads can be energized with DC, the arrangement of (a) is satisfactory. When AC as well as DC must be distributed, a central inverter is added, as in (b), and the AC and DC emergency loads are fed separately.*

(c) Technical Considerations

In general, when emergency power is discussed, it is assumed to be replacing normal power; that is, the assumption underlying most codes and standards is that power must be supplied to selected loads within the building because of a utility power outage. In good-practice design, cognizance must also be taken of situations in which normal power has not failed, and an outage is localized because of an in-building equipment failure. This aspect of design—reliability—is left to the designer and owner to decide in the context of a given building situation. Some of the arrangements discussed here differentiate between the nature of outages—that is, a utility or general outage versus an equipment or local outage. An exception to this generalization occurs with health-care facilities, where *NEC* (in Article 517) specifies an internal electrical design that largely covers both types of outages down to the distribution level. Refer to the referenced *NEC* article for further information.

An emergency system includes all devices, wiring, raceways, and other electrical equipment, including the emergency source that is intended to supply electric power to the selected load(s). An important aspect of code requirements permits the use of a single power source for (1) emergency, (2) legally required standby, and (3) optional standby systems, provided that it is equipped with automatic selective load pickup and load-shedding equipment that will ensure adequate power to the three types of systems in the order of priority stated (1, 2, 3).

1. Where emergency loads are not substantial, a storage battery arranged to be connected automatically on power outage may be used. Where all emergency loads can be operated on

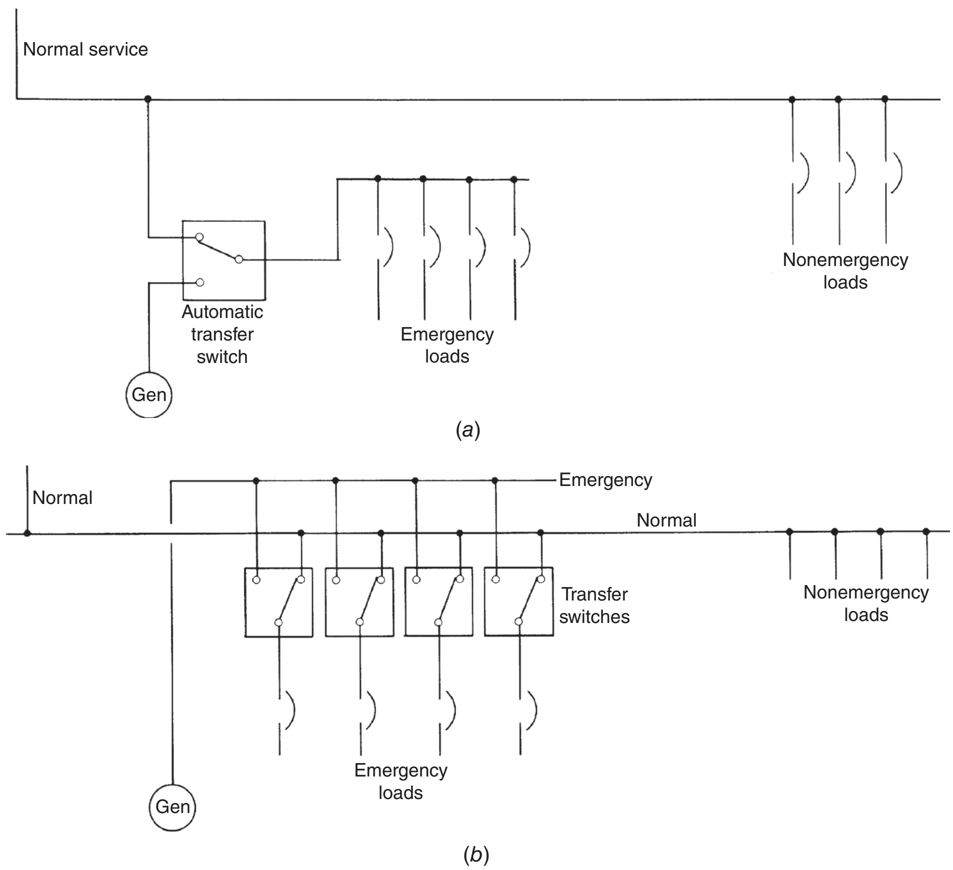


Fig. 29.27 *Alternative arrangements of emergency/normal power feed. In (a) a single transfer switch serves the normal power and transfers to the generator upon power failure. In (b) there are multiple smaller transfer switches, thus reducing the chance of a single equipment failure faulting out the entire emergency power system.*

DC, the arrangement of Fig. 29.26*a* is used. If AC power is required, the arrangement of Fig. 29.26*b* can be utilized.

2. Where emergency loads are larger than can be practically supplied by a battery installation, and where a start-up and power transfer time of up to 10 seconds is tolerable, a generator set is employed. A combination of emergency sources may be used in a single building. For instance, a generator can supply bulk power loads and a battery installation selected lighting loads.

   The system can be arranged with a single transfer switch that senses normal power loss, as in Fig. 29.27*a*, or it can use multiple switches, each one of which will sense power loss *at its downstream location*, as in Fig. 29.27*b*. The latter system provides greater power reliability, provided that the design is such that the emergency power uses an independent power path to the transfer switches. Otherwise, a fault in a junction box or an item of equipment that interrupts normal power downstream will also prevent emergency power from reaching that point.
3. Some codes permit the use of two separate electric services in lieu of a normal service plus an emergency source, provided that the two sources are truly independent—that is, come from different utility transformers or feeders; enter the building at different points and, preferably, from different directions; and use separate service drops or laterals. The point is that the type of reliability desired can be obtained only by minimizing the possibility of a single event interrupting both services. The usual arrangement is for one such utility service to be normal and the other standby.
4. The least reliable arrangement is one in which the emergency loads are connected ahead of the main disconnects and are so arranged that a downstream fault within the building will not affect these items. This situation is illustrated in the riser diagram of Fig. 29.24, where the stair and exit panel (which supplies egress lighting) and the fire alarm panel are connected ahead of the building main disconnect and protected with their own fuses. This arrangement is permitted only for Legally Required Standby Systems (*NEC* Article 701) and not for Emergency Systems as defined in *NEC* Article 700. The items that may be connected ahead of the main service equipment are generally limited to emergency lighting, fire alarm, fire pumps, standby power equipment, and other alarm and protective equipment, each of which must be provided with a separate disconnect means and overcurrent protection (see *NEC* Article 230-82).

   This power arrangement can do nothing in the event of a power outage. It was once very common, but is now falling into disuse as a result of more stringent codes and its serious shortcomings.
5. The *NEC* recognizes a category of equipment for emergency illumination called *unit equipment*. These types of devices, discussed and illustrated in Section 17.31(d), consist of individual self-contained packages with a battery, charger, and light source *permanently* mounted and wired at required locations. The panel device feeding these units should be clearly identified.

References and Resources

Numerous standards from the NFPA dealing with emergency power systems (and other aspects of electrical system design) are identified in Section 29.21b.

McGuinness, W. J., B. Stein, and J. S. Reynolds. 1980. *Mechanical and Electrical Equipment for Buildings*, 6th ed. John Wiley & Sons. New York.

C H A P T E R 30

Photovoltaic Systems

30.1 A CONTEXT FOR PHOTOVOLTAICS

A PHOTOVOLTAIC (PV) SYSTEM PRODUCES electricity through direct conversion of incident solar radiation (primarily radiation in the visible spectrum—light). This is an incredibly useful transformation process. Virtually every building of any size or function requires and consumes electricity. Solar radiation is a renewable resource, which will generally impinge upon a building in useful quantities in most climate zones (whether or not the building uses it for beneficial purposes). PV then seems an ideal design solution—providing a needed energy form from an otherwise often unused resource. In an ideal world, every building would have a PV system. Unfortunately, the economics of PV power production dampen this idyllic picture. PV power production generally costs an owner more than utility-provided power, even considering reasonable life-cycle costing scenarios. In fact, the economics are currently such that PV systems for buildings are the exception rather than the rule. There has long been hope that the economic picture would change through the evolving availability of much cheaper PV components. This has not really happened to the extent anticipated. In fact, recent volatility in the source of PV module supplies has led to some questions regarding long-term product quality. Any future shift in PV system economics will likely occur mainly as the result of higher cost for competing electricity sources (utilities) and/or rebates or incentives from governments or utilities for distributed, greener power sources.

PV electric power systems, which until the middle to late 1980s were little more than a curiosity in the United States because of their very limited applicability and discouraging economics, have recently begun to make a noticeable impact on the commercial electrical power scene. This has come about for several reasons, the most important of which are federal government–financed research and development, and state and federal government–sponsored legislation in the electric utility field. The PV Manufacturing Technology project (PVMaT) involving the U.S. Department of Energy (DOE) and 20 private companies (launched in 1990), plus the 1992 Building Opportunities in the United States for Photovoltaics (PV:BONUS) program (also sponsored by the DOE) resulted in the reduction of PV module costs from upwards of \$5.00 per watt to about \$1.50–2.50. In addition, these initiatives spurred the development of new PV module materials, construction techniques, and product forms; increases in PV module efficiency; and a sharp overall decrease in the cost of power produced from about \$0.50–\$1.00 per watt to about half that amount, depending upon the system configuration. The legislative impetus has taken the form of utility deregulation and specific legislation requiring utilities to purchase power produced by small, private installations.

Several recent government efforts to foster the development of PV systems are under way. The (U.S.) Photovoltaic Industry Roadmap is an industry-led effort to help guide domestic PV research, technology, manufacturing, applications, markets, and policy. The Roadmap presents the intended direction of the PV industry, its critical partners, and U.S. government programs for the years 2000 to 2020. The U.S. PV program is associated with the International Energy Agency's (IEA) Task 16 effort focused upon PV systems for buildings. The potential market for building-integrated PV systems in the United States is enormous, and many companies are beginning to work at the development and commercialization of building-integrated PV components and systems. Increasing and substantial U.S. sales of PV roof shingles are indicative of this potential. Green building design efforts are also increasing interest in PV systems, with LEED new construction credit provided for renewable energy resources and for green power.

The 1978 federal Public Utilities Regulatory Policy Act (PURPA) required electric utilities to buy electric power at a price equal to the costs they avoid by not having to produce that power. The utilities generally interpret that "avoided cost" as fuel cost only, without considering other avoided costs such as additional plant construction. As a result, energy is often bought under this law at about \$0.03/kWh by the same utilities that sell energy at \$0.08–0.15/kWh. This spread does not encourage the construction of grid-connected PV installations (see Section 30.5*b*). Subsequently, many states adopted net-metering laws that reduced this price imbalance. In this arrangement, the utility buys power during peak PV generation periods (see Fig. 30.1) at the same rate at which it sells power. At the end of a billing period (usually 1 month), any difference between utility-purchased and customer-purchased power is paid for at the given rates (i.e., if the customer used more power than he/she generated, that power is paid for at the conventional utility rate). Conversely (and less commonly), if the customer generated more power than was used, the utility would buy it at the avoided-cost rate.

The net-metering arrangement is attractive economically to both utility and user. A utility buys power that offsets its peak afternoon load, which is particularly severe in warm weather, and sells power in its off-peak morning and evening periods. A residential customer sells power at the PV installation's peak output, which is also usually a period of low user consumption (Fig. 30.1), and buys it back at the same price in the evening, when PV output is low but power demand is high. The arrangement removes the necessity for an expensive battery installation that, in a stand-alone system, provides power during periods of low PV energy production.

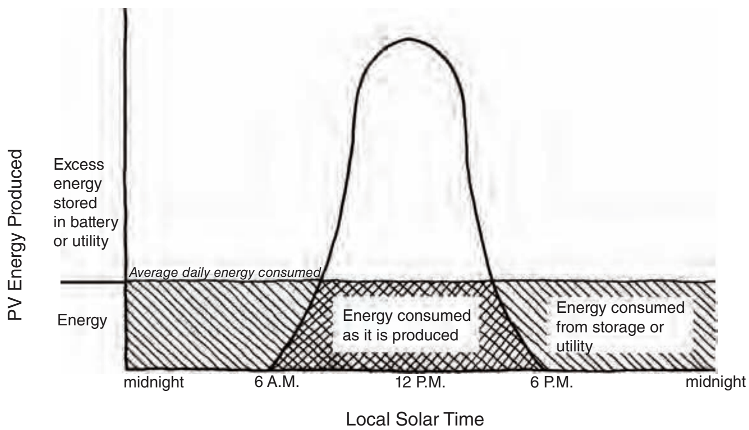


Fig. 30.1 *Graph representing electricity produced and used by a residence equipped with a PV array. Daily energy use is shown as a uniform average over a 24-hour period to indicate overall quantity but not an actual usage pattern. The bell-shaped PV energy production curve is centered on solar noon and extends from sunrise (solar 6:00 A.M.) to sunset (solar 6:00 P.M.). The area of the bell curve above the average consumption line indicates electricity that would be purchased by a utility in a grid-connected system or stored in batteries in a stand-alone system. (From Harris, Miller, and Thomas. 1985.* Solar Energy Systems Design, *p. 715. Reprinted with permission of John Wiley & Sons, Publishers. Redrawn by Amanda Clegg.)*

This advantage, combined with other advantages such as having a nonpolluting power source, has led to a large increase in grid-connected installations. Indeed, the attractiveness of having a green, environmentally beneficial electric power supply is so great that a number of electric utilities have instituted a (primarily residential) PV installation program in which the utility installs and maintains a PV system on the customer's premises (usually on the roof), for which the customer pays a nominal surcharge on the monthly electric power bill. The advantages of net billing, however, are available only to customers who initiate and maintain a PV system themselves.

30.2 TERMINOLOGY AND DEFINITIONS

A generally accepted terminology has developed in the PV field. The list that follows contains common terms and their accepted definitions. Particular attention should be paid to two terms that are often incorrectly used interchangeably: insolation and irradiance. *Irradiance* is the amount of solar *power* impinging on a specific area, usually measured in units of watts per square meter—and represents an instantaneous value. *Insolation* is the amount of solar *energy* received by a given area, measured in Wh/m^2, kWh/m^2, Btu/ft^2, or MJ/m^2 (with 1 kWh/m^2 = 317.2 Btu/ft^2)—and represents a time-averaged value.

Avoided cost. The minimum amount an electric utility is required to pay an independent power producer under the Public Utilities Regulatory Policy Act of 1978.

Balance of system (BOS). All components other than the PV modules themselves, which include the system electronics, support structure, and storage.

BIPV. Building-integrated photovoltaic (system); a PV system with cells/modules incorporated as an integral part of the building envelope (rather than simply tacked on to the building shell).

Blocking diode. A diode used to block reverse flow of current into a PV source circuit.

Interactive system. A PV system that operates in parallel with the electric utility lines and may be designed to deliver power to the utility.

Inverter. Commonly known as a *power conversion system* (PCS), an inverter is a device that changes direct current (DC) to alternating current (AC). An inverter is not the same as a power-conditioning unit (PCU).

Panel. A collection of modules mechanically fastened together, wired, and designed to provide a field-installable unit.

Peak sun hours. The number of hours per day at an irradiance of 1 kW/m^2 that is equivalent to the total daily insolation energy.

PV array. A mechanically integrated assembly of modules or panels with a support structure and other components, as required, including tracking apparatus where used, forming a power-producing unit.

PV cell. The basic PV device that generates electricity when exposed to solar radiation.

PV module. The smallest complete, environmentally protected assembly of PV cells and other components normally sold by a manufacturer; comprising several (or many) PV cells.

PV system. All the components and subsystems that, in combination, convert solar energy into electrical energy suitable for connection to a load.

Stand-alone system. A PV system that supplies electrical energy without interconnection to any other power source.

Thick-crystal photovoltaics. The most common commercial type of PV material.

Thin-film photovoltaics. PV devices made of a semiconductor material, such as copper indium diselenide or amorphous silicon, a few micrometers thick, deposited on substrates of glass, ceramic, or another compatible material.

30.3 PV CELLS

The production of an electric charge when solar radiation (primarily light) strikes some metallic surfaces has been a recognized physical phenomenon since the mid-nineteenth century. Around 1905, Einstein established a mathematical basis for what has come to be known as the *photoelectric effect*. The explanation of this effect, in simplified and qualitative terms, is approximately as follows. Light exhibits both wave characteristics and characteristics of a stream of energetic particles called *photons*. When a photon strikes a photoelectric metal surface, it dislodges a single electron from its normal orbit, causing a charge to appear. When pure silicon is exposed to an intense stream of photons, as from sunlight, a large number of electrons are dislodged from their orbits and proceed to wander about the crystal lattice structure of the silicon crystals. By a process called *doping*, impurities are deliberately added to pure silicon to create a P–N (positive–negative) junction, across which the electrons flow to create an electric current and give the doped silicon the properties of a semiconductor. If the semiconducting doped silicon is exposed to light and the negative and positive sides of the junction are connected through a load, an electron flow (a current) commences from the negative side of the junction to the positive side, doing work on the load. Work, of course, is energy. The energy comes from the fast-moving photons (light) and is imparted to the dislodged electrons by impact. The overall effect is to create a current flow proportional to the intensity of photon bombardment—that is, proportional to light intensity. Figure 30.2 is a schematic representation of this process.

The photons in solar radiation are not uniformly energetic. It has been found experimentally that a photon must have an energy of at least 1.08 electron-volts (corresponding to a wavelength of 1150 nm) to dislodge an electron. Photons at longer wavelengths do not have sufficient energy to create the photoelectric effect. Because shorter-wavelength photons are more energetic, the entire visible spectrum (light) is useful in PV action, the magnitude of current produced depending upon the intensity of light. According to Einstein's PV theory, a single photon can only dislodge a single electron; thus, any photon energy in excess of the minimum (dislodgement) level is dissipated as heat. For this reason, PV cells generate heat as well as electricity, and some means of heat collection or dissipation is required in practical PV array construction. Commercial PV cells operate at an overall insolation-to-electric energy conversion efficiency of around 8% to 12%. By layering different strata of semiconductor material, each of which is sensitive to a different limited-frequency bandwidth (called *bandgap*), efficiencies as high as 35% to 40% can be achieved. Economic considerations, however, have limited today's commercial PV modules to a maximum of two layers with a maximum conversion efficiency of about 12%.

As mentioned previously, intensive research and development work on solar cell construction has yielded a generation of PV materials that are variously referred to as *thin-film technology* and *polycrystalline technology*, using various copper and cadmium compounds and amorphous rather than large crystal silicon modules. These materials offer higher efficiencies, can be manufactured into large elements, and, because they do not require a glass cover, can be integrated into standard building

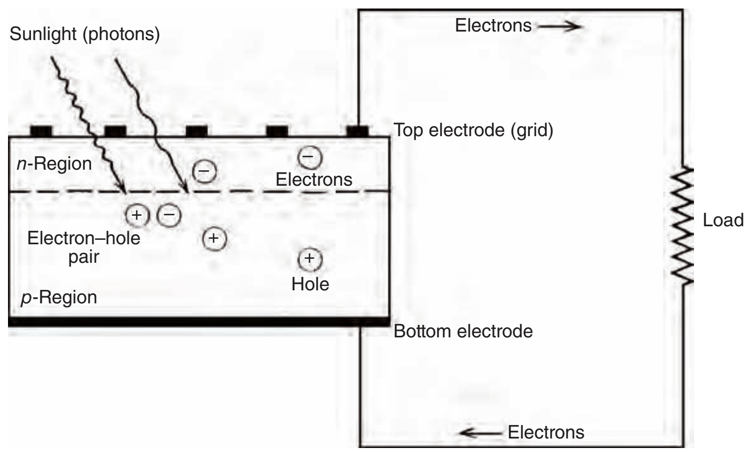


Fig. 30.2 *Schematic drawing showing the conversion of solar energy to electrical energy by a PV cell. Photons from solar radiation dislodge electrons in the silicon semiconductor surface, creating a positively charged "hole." The P–N junction creates an electric field that "sweeps" electrons across the junction. When the top and bottom electrodes are electrically connected through a load, an electric current flows. This current is capable of doing work (supplying energy). (From Meyers, ed. 1983.* Handbook of Energy Technologies. *Wiley-Interscience. Reprinted with permission.)*

material formats (as building-integrated PV elements). Typical data for two commercial products using this technology are:

Amorphous Silicon Module
Dimensions: 2 ft × 4 ft × 2 in.
(610 mm × 1220 mm × 50 mm)
Weight: 33 lb (15 kg)
Electrical: 50 W, 72 V, 0.7 A

Thin-Film Polycrystalline Module
Dimensions: 2 ft × 4 ft × 2 in.
(610 mm × 1220 mm × 50 mm)
Weight: 22 lb (10 kg)
Electrical: 75 W, 17 V, 4.5 A

These second-generation PV materials have high efficiency and a flexible physical format, distinct advantages over the older, large crystal silicon wafer elements. However, the latter are cheaper, *extremely* hardy, reliable, and long-lived, as has been demonstrated in many satellite and space vehicle applications. The newer units are initially somewhat unstable and have a shorter life than the large crystal silicon units.

The PV cell is the smallest electricity-producing unit in a PV system. Cells are not sold individually as commercial products but are arranged by the manufacturer into modules. A module is the smallest commercially available electricity-producing increment. The size of a module and the number of modules required to produce a desired electrical output depend upon the type of PV cell used, the manufacturer's product line, and the intent of the PV system designer. If more than one module is required, as is often the case, multiple modules are assembled on site into arrays. A module is a self-contained product; an array is a field-assembled group of modules.

30.4 PV ARRAYS

A PV array is a complete and connected set of modules mounted and ready to deliver electricity. Two basic array arrangements exist: stationary and tracking. Building-mounted arrays are typically stationary and often have the advantage of not requiring a substantial support structure, although even a simple roof mounting on a pitched roof can be expensive due to the labor cost involved. The materials usually used for ground-mounted array structures are concrete, galvanized steel, and aluminum. Wood and painted iron are not recommended because of their high maintenance costs and relatively short life. The design of an array mounting will depend upon the array size, weight, mounting angle, and wind loads and is therefore unique to each installation. Mounting on a wooden pole or steel pipe with a single support point is limited to relatively small arrays in low-wind areas because of the stress on the support arrangement. Several typical fixed mounting arrangements are shown in Figs. 30.3 through 30.5.

The angle, measured from the horizontal, at which a flat-plate collector is mounted is known as the *tilt angle*. For a stationary (nontracking) array,

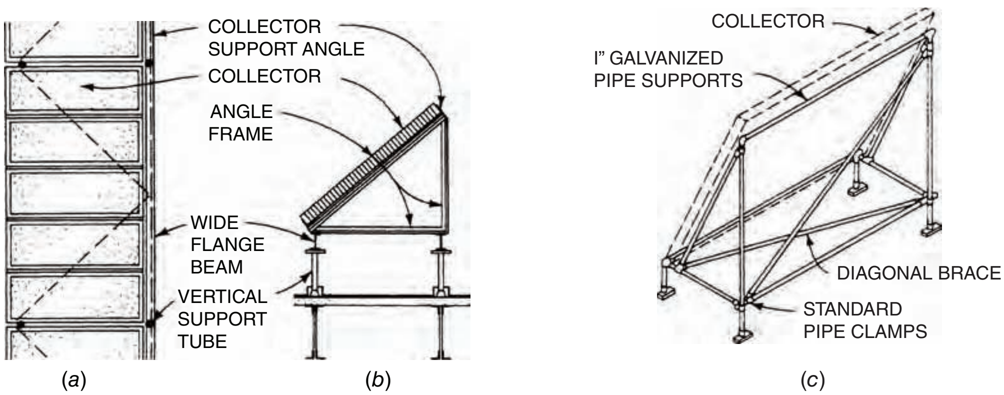


Fig. 30.3 *Typical mounting techniques for PV arrays. (a) Plan of the arrangement for mounting large arrays on a horizontal surface. (b) Section through (a) showing mounting and arrays. (c) Simple pipe rack mounting for a small array. For all installations, ensure that wind and seismic loads, snow collection, and array cooling have been considered. (Diagrams reprinted with permission from* Architectural Graphic Standards*, 10th ed. 2000. John Wiley and Sons, Publishers.)*

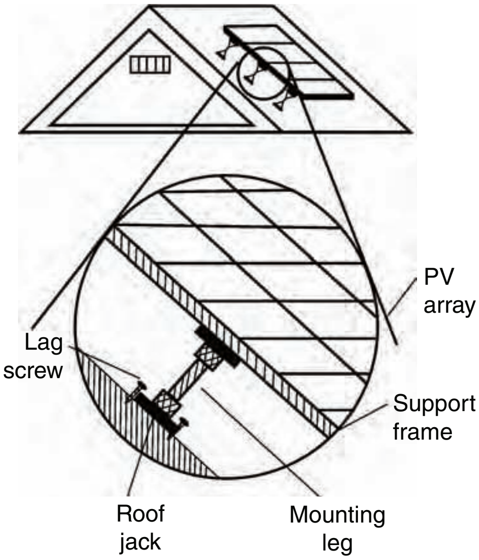


Fig. 30.4 *Typical roof mount for a PV array. Array tilt and azimuth can be adjusted through the mount design. Exercise caution in snow areas so that accumulating snow does not block the array and does not slide off onto pedestrians. (From* Stand-Alone Photovoltaic Systems. *Sandia Laboratories. 1995.)*

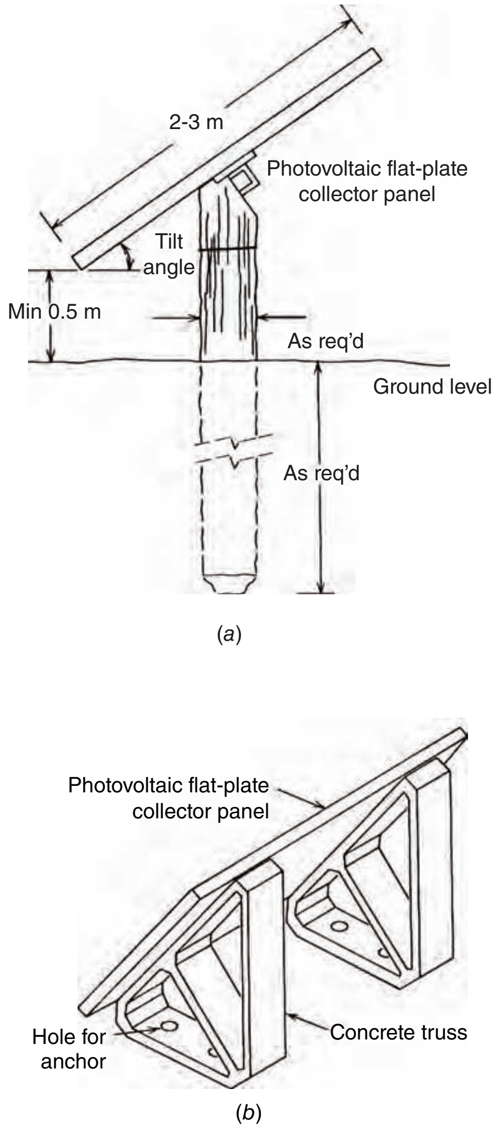


Fig. 30.5 *Flat-plate PV collector support structures. (a) Wooden-pole torsion tube support. (b) Concrete truss support. (From Meyers, ed. 1983.* Handbook of Energy Technologies. *Wiley-Interscience. Reprinted with permission.)*

total *annual* insolation is maximum for a tilt angle equal to the latitude of the site. To maximize winter insolation, when the sun is lowest, the tilt angle can be increased to latitude plus 15°. Conversely, to maximize summer insolation, when the sun is highest, the tilt angle can be reduced to latitude minus 15°. The tilt angle chosen for a stationary array depends upon PV output usage schedules, the amount of insolation for the months of the year, and economic considerations.

Tracking arrays follow the motion of the sun and thereby substantially increase the insolation per unit area of solar cells. Single-axis tracking follows the sun's motion from east to west while maintaining a constant array tilt angle. This type of tracking can increase insolation by 35% to 50% throughout the year and is most effective at low latitudes. Completely passive, sealed compressed gas, single-axis tracking drives are available for small to medium-sized pole-mounted arrays in low-wind areas. Where wind velocity is high, a motorized drive using PV-generated power may be necessary. Dual-axis tracking (following solar altitude and azimuth) for flat-plate collectors and altitude tracking for various designs of concentrating collectors are beyond the scope of this book.

30.5 PV SYSTEM TYPES AND APPLICATIONS

There are two basic types of PV systems: *stand-alone* and *grid-connected*. These names well describe their essential characteristic, which is their relationship to an external source of electricity such as a utility connection.

(a) Stand-Alone Systems

A stand-alone system is just that; it is isolated from any outside electrical connections and is designed to do a carefully defined specific job. Stand-alone systems are the oldest PV installations because they were essentially the only solution to the problem of electrifying a remote and/or unattended load. Stand-alone installations typically supply electricity for sign lighting, railroad crossing lights, unattended pumps, lighthouses, unattended navigational aids, microwave repeaters, motor homes, sailboats and yachts, isolated small residences, and the like. The common characteristic of all these installations is the impossibility or impracticality of feeding them from a utility grid. When loads become larger than can be supplied by a practical solar array (from a physical or economic viewpoint), and particularly when the peak load is periodic rather than continuous, a fuel-powered generator is usually added to the system. Such a system is known as a *hybrid stand-alone system* and is used frequently for remote residences where the connection charge levied by the local utility is so large that a PV system is an economical and environmentally friendly solution to the problem of providing electricity. Schematic diagrams of stand-alone system types are shown in Figs. 30.6, 30.7, and 30.8.

The difference between the systems shown in Figs. 30.6 and 30.7 is the use of an energy storage medium—in most cases, a battery. The *direct-connected* system in Fig. 30.6 is applicable only with loads that tolerate variable power levels ranging from zero at night to maximum at solar noon. The most common of these is water pumping, using a DC motor to drive a positive displacement (piston) pump. Such installations are frequently used to fill elevated water tanks because a slow, interruptible fill rate does not adversely affect the water system's usability.

The vast majority of stand-alone systems are assembled as shown in Fig. 30.7, using a storage battery to store excess electricity produced during peak insolation hours for use during periods of reduced solar resource (cloudy days) and full darkness (nighttime). With proper component selection, as is discussed in detail in subsequent sections, stand-alone PV systems can be used to adequately supply remote year-round residences, small mercantile establishments, and other off-grid loads.

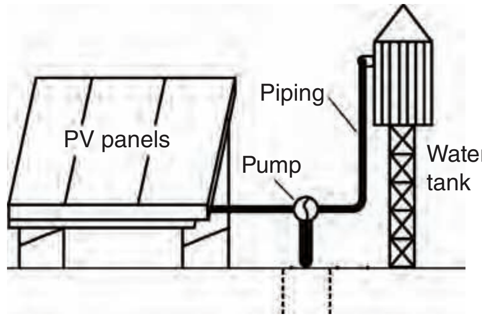


Fig. 30.6 *Typical direct-connected PV installation feeds electric power to a positive-displacement pump that pumps water into an elevated tank.*

A stand-alone system may contain a DC-to-AC inverter if any of the loads require AC that cannot be supplied by an equipment-specific inverter. The choice of whether to use a single central inverter or distributed smaller inverters is largely an economic decision. Fluorescent lamps, a reasonably efficient source of light, are available with integral inverter ballasts. Some kitchen appliances and power tools, however, are not readily available in a DC or battery-powered format, although that situation is rapidly changing and warrants careful investigation during system design.

The hybrid stand-alone system shown in Fig. 30.8 is similar to the stand-alone system in Fig. 30.7, with the addition of a small AC generator.

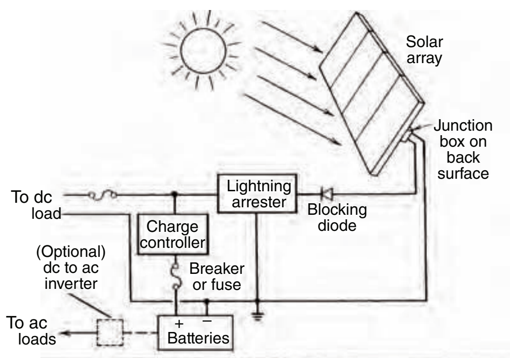


Fig. 30.7 *Schematic diagram of the most common type of stand-alone PV installation. The blocking diode prevents reverse current flow when the battery voltage exceeds that of the PV array. The charge controller prevents overcharging of the battery and excessive current drain. If AC loads are present, a DC-to-AC inverter is added, sized as required. (From Harris, Miller, and Thomas. 1985.* Solar Energy Systems Design. *Reprinted with permission of John Wiley & Sons, Publishers.)*

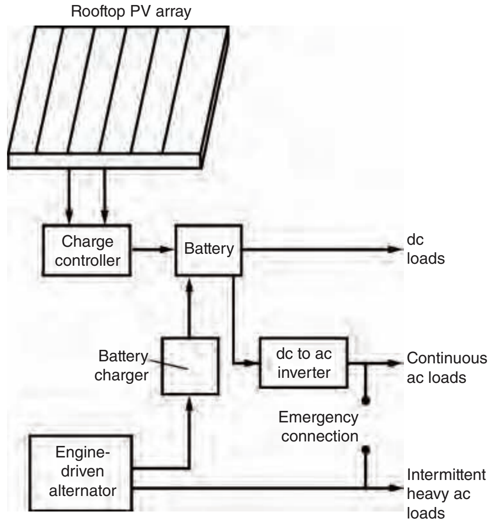


Fig. 30.8 *One arrangement for a hybrid stand-alone PV system (control and safety devices are omitted for clarity). A diesel-, gasoline-, or propane-driven AC generator (alternator) supplies large, intermittent AC-only loads, whereas the PV array and battery supply DC loads and continuous AC loads through an inverter. During long, cloudy periods the alternator can charge the battery and, via an emergency connection, can also supply the regular AC loads. Other arrangements are possible, such as using a larger inverter to supply an all-AC system, with the alternator supplying intermittent heavy AC loads and all loads during low-battery periods.*

This type of system, as noted previously, is used where operation of a heavy AC load, such as a clothes washer or another relatively large AC motor–driven appliance, is necessary. Where these loads are fairly continuous, as with refrigeration and air-conditioning equipment, a larger PV system should be considered. A continuously running engine–generator set is a source of noise and air pollution, and the ongoing consumption of a fossil fuel resource in such an installation makes it contradictory in spirit to a completely silent, pollution-free, renewable-resource-driven, solar-powered PV installation.

(b) Grid-Connected Systems

Prior to the advent of net-metering, the number of stand-alone PV systems in areas served by electric utility grids was small because of the overwhelming economic advantage of purchased power. Even today, with net-metering, the payback period for an initial PV system investment seldom justifies an installation on purely economic grounds, although the continuous development work in PV materials may change that situation.

In a stand-alone arrangement, battery costs over the life of the system can exceed those of the PV array. Lead–acid batteries are relatively cheap but have a short life; nickel–cadmium batteries have a longer life but are much more expensive. By replacing the batteries that furnish energy storage and carryover in a stand-alone system with a utility connection that effectively serves the same purposes, and by taking advantage of the economies available from building-integrated PV elements (see Section 30.5*c*) in new construction, an economical PV system with reasonable payback can be constructed. A schematic diagram of one such system arrangement is shown in Fig. 30.9.

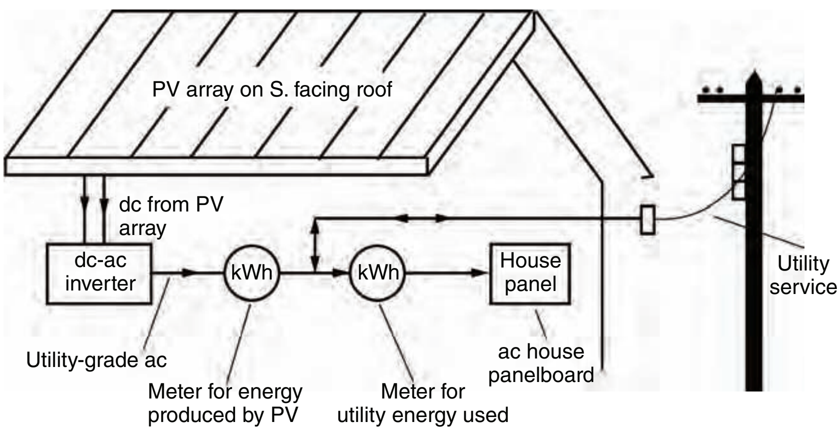


Fig. 30.9 *Schematic drawing of a grid-connected PV system arranged for net-metering. Power from the array is converted from DC to utility-grade AC power (constant voltage and frequency; low harmonic content) by the inverter and fed to the utility connection through a kWh meter that measures the electricity sold to the utility. The second (utility company) meter measures the total power used by the structure. The difference in meter readings represents the positive or negative (credit) utility billing.*

The inverter shown in the diagram creates utility-grade AC from the PV array DC output and feeds it to the utility through an electric (kWh) meter. The inverter shown is equipped with a safety cutoff that instantly disconnects the PV system from the grid if a utility outage is sensed. This is a requirement of the electric utilities to ensure that their maintenance personnel are not endangered by PV electric power being fed into an apparently deenergized line.

The power company supplies house power through a second meter, as shown. In net-metering, the difference between the readings of the two meters is either billed to the consumer at the normal utility rate or credited to the consumer at the avoided-cost rate, depending on which meter reads higher. A consumer will notice no difference whatever in electric service, except in the lower, or possibly even negative, electric utility bills.

More recently, to encourage wider use of nonpolluting PV power, some utilities have permitted the installation of small, individual PV modules in existing buildings. These units plug into convenience outlets in the building, supplying power to the building itself. Any excess electrical energy not required by the structure is fed back into the utility via their reversible energy meter. This arrangement is shown schematically in Fig. 30.10. Each PV module (panel) is equipped with a built-in, high-quality inverter that produces utility-grade power and is equipped with the safety devices described previously. A common commercially available unit of this type is rated at 100 W peak, 85 W nominal, 120 V, 60 Hz; measures approximately 2 ft × 4 ft × 4 in. (610 mm × 1220 mm × 50 mm); and weighs 25 lb (11 kg). The advantage gained with these units is that a user can begin with one or two modules and then expand as desired, without a relatively high first cost investment and without a centralized installation requiring professional construction and electrical personnel. Some power companies require separate disconnect switches for each PV unit rather than relying only on physical disconnection of the unit plug from the wall outlet.

The National Renewable Energy Laboratory (NREL) developed and maintains a design tool for analysis of grid-connected PV systems. The tool is PVWatts, and it is freely available via the Internet (in fact, it runs online with no need for a download). Performance and cost analyses can be quickly run for a fairly wide range of locations, array orientations, and array tilts. As with most easy-to-use design tools, there are a number of assumptions built into PVWatts—but all are noted, and most can be modified (either explicitly or implicitly) by the user.

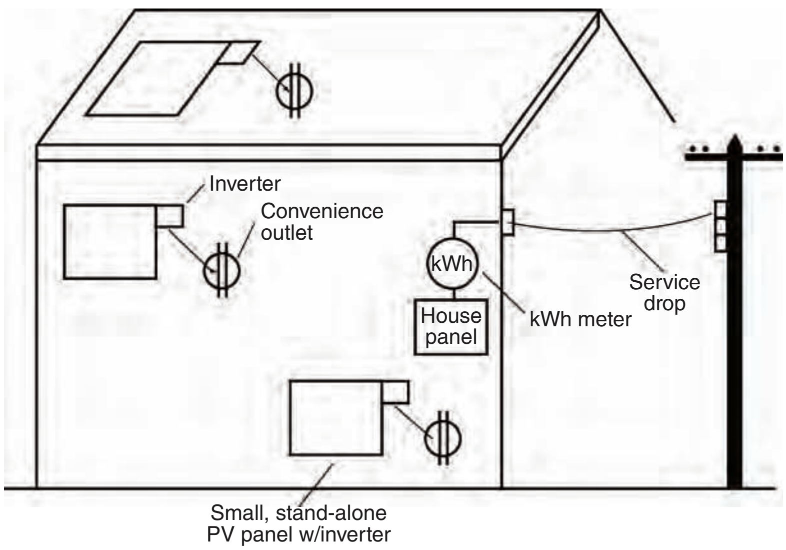


Fig. 30.10 *Schematic drawing of a grid-connected PV system using small, distributed PV arrays connected to the house distribution system via convenience outlets. In this arrangement, the utility meter is unratcheted (reversible) so that excess PV-produced electricity reverses the power company's meter. Any net monthly credit is calculated at the avoided-cost rate.*

(c) Economic Considerations

Economic issues can be complex, and they are often the deciding factor in the choice between full PV, a PV-grid combination, and a conventional (grid) electric service. Among the cost factors are:

- Cost of a grid connection.
- Cost of power from the grid.
- Life-cycle cost of each component of the system over the life of the entire installation. This is necessary because the life span of individual components varies sharply; PV modules last about 20 years, batteries about 5 years, electrical components 10 to 20 years (or more), PV module mountings 15 to 25 years, tracking mechanisms (if used) 5 to 10 years, and so on.
- Life-cycle maintenance costs (parts and labor) for each item.
- Financing costs.
- Cost credits for PV systems, including such items as use of a system battery as an uninterruptable power supply (UPS) source for computers and peripherals, savings from avoided grid-power service interruptions, and construction cost credits when PV modules are used in lieu of building elements.

The last factor has taken on considerable importance in recent years with the development of building-integrated PV (BIPV) elements. A traditional PV installation consists of PV modules mounted near or on a building or facility. Often, the modules are roof-mounted if a roof surface of appropriate orientation (generally south-facing) and sufficient size is available. The development of thin-film amorphous silicon modules permits incorporation of PV cells into assemblies that can replace traditional building construction elements (typically in the form of roof panels, roofing tiles, wall panels, or skylights). These assemblies fulfill the dual function of producing electricity and weatherproofing the building envelope. In the jargon of design intent, they are *transformer* elements, replacing historically used barrier or filter elements. In such cases, only the difference in cost between standard construction and BIPV construction should be taken as an additional cost of the PV system.

30.6 PV SYSTEM BATTERIES

Batteries are required in a stand-alone system to store excess PV-produced electricity (from high-production periods) for use during peak electricity consumption periods (the pattern illustrated in Fig. 30.1). For residential installations, there is usually almost no coincidence between these two time periods because PV output peaks at solar noon, whereas residential usage peaks in the evening and is low at noon. In comparison, commercial stand-alone PV installations such as off-grid stores, shops, cottage industries, and the like have a much higher coincidence. This means that during normal, everyday use, the drain on the battery is shallow, and a cheaper battery will frequently suffice. These considerations are expanded in the system design discussions in Sections 30.8 and 30.9.

A PV system battery is usually expected to be capable of supplying most or all of an installation's electrical requirements for a given period—usually 3 days of cloudy weather if no other specific-use data are available. This means that the battery selected:

- Must be capable of repeated discharge to 20% capacity or less without injury
- Must be designed to accept slow, lengthy recharge

In addition, the battery:

- Should have long life
- Should be suitable for the physical conditions in which it will be used (i.e., space, ambient temperature, ventilation, and maintenance availability)

Pure lead automobile batteries (also known as *lead–acid* batteries) are not suitable for PV systems because they are designed for rapid, shallow discharge (engine starting) and very rapid recharge. If such a battery is repeatedly discharged more than about 20% (shallow discharge), or if it is not completely recharged after discharge, its life will be extremely short. Batteries made for use in electric vehicles such as golf carts and forklifts are constructed with heavy plates and are designed for the deep-cycle discharge needed in PV systems. Most of these are flooded batteries, meaning that the plates must be completely covered with electrolyte to prevent damage. This requires frequent maintenance, making flooded batteries unsuitable for unattended sites.

Lead–calcium batteries are almost maintenance-free, rarely requiring addition of water or electrolyte. As a result, they are frequently used in unattended systems. They do not cycle as deeply as heavy-plate, deep-cycle units, and this must be considered during design.

Sealed batteries are completely maintenance-free. They are frequently constructed with a gel-type electrolyte that does not "boil" off on recharge and therefore needs no replacement. This makes them ideal for unattended sites, provided that they are specifically designed for deep-cycle service (80% discharge) and are so labeled. Most maintenance-free batteries are shallow-cycle units and therefore are unsuitable. An important characteristic of sealed units is that they require very accurate charge and discharge control to prevent overcharge or overdischarge, or over-rapid charge or discharge. Any of these conditions severely shortens battery life. As a result, gel-cell batteries require the use of a high-quality charge controller.

Lead–antimony batteries are very sturdy and tolerate deep discharge and slow or rapid charge while maintaining their rated life. They require occasional water replenishment and adequate ventilation to disperse gases created during charging cycles.

Nickel–cadmium batteries are highly desirable in PV systems because they are maintenance-free, can be discharged to essentially 100% of capacity without injury or shortening of life, are much less temperature-sensitive than lead–acid batteries, and have a longer life. Their principal drawback is their high price. Nickel–cadmium batteries should not be shallow-discharged because they tend to develop a "memory" of the discharge cycle and after many shallow cycles may not supply sufficient current for a deep discharge. Therefore, in essentially clear-sky climates, where a 3-day period of cloudiness is rare, nickel–cadmium batteries may not be applicable because storage sized for a 3-day system supply would normally be operating on shallow discharge.

Additional considerations in battery selection include:

Temperature. Lead–acid battery capacity declines with temperature. Nominal battery capacity ratings are referenced to a temperature of 77°F (25°C). Batteries operating at lower temperatures should be derated (in the absence of specific manufacturer's recommendations) as follows:

Ambient Temperature	***Derating Factor***
70°F (21°C)	0.96
60°F (16°C)	0.90
50°F (10°C)	0.84
40°F (4°C)	0.77
30°F (−1°C)	0.71
20°F (−7°C)	0.63

It is important to note that a discharged lead–acid battery contains essentially water and therefore freezes at about 30°F (−1°C). A fully charged battery will not freeze until the temperature dips below 0°F (−18°C). Nickel–cadmium batteries are much less affected by temperature.

Voltage. Battery terminal voltage varies with its state of charge, ranging for a 12-V battery at 77°F (25°C) from approximately 15 V at full charge to just over 12 V immediately after a deep discharge. If the battery is not charged immediately, voltage drops to a low of slightly over 11 V.

Life. A properly maintained deep-cycle lead–acid battery should last for a minimum of 5 years. A nickel–cadmium battery should last 1.5 to 2 times as long.

Rating. The manufacturer's stated ampere-hour (A-H) rating of a battery refers to a single continuous low-rate discharge under laboratory conditions. The actual field-use A-H capacity of a battery depends heavily upon the discharge rate, and it is this figure, as calculated for the particular installation, that should be used to compare batteries of the same type. All reputable manufacturers have readily available discharge curves that show voltage and duration at different discharge rates.

The basic storage battery is rated at 12 V, although 6-V units are available. Figure 30.11 shows typical battery connection arrangements for the most common system voltages, which are 12, 24, 48, and 72 V. Table 30.1 shows some typical physical data for batteries.

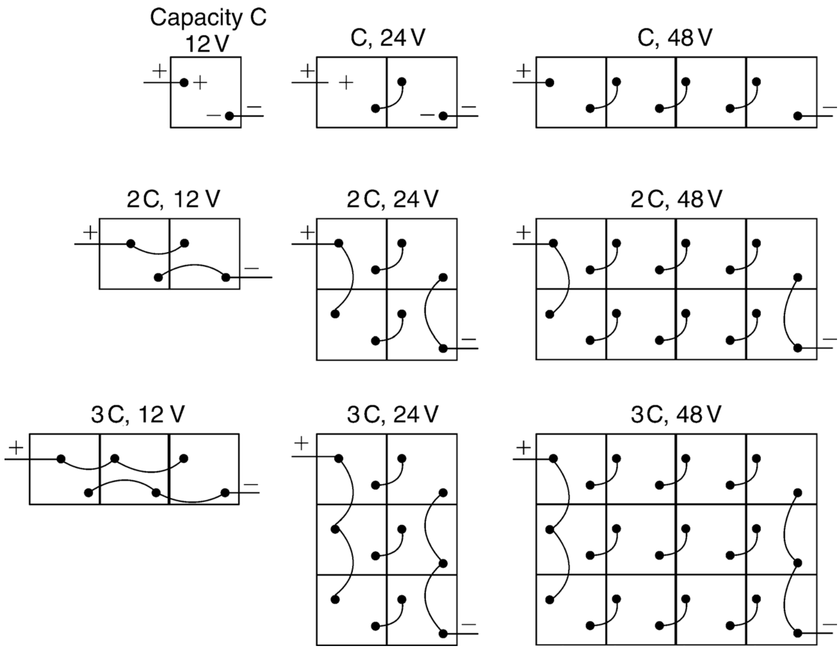


Fig. 30.11 *Wiring arrangements for 12-V battery packs to obtain increased capacity, increased voltage, or both.*

30.7 BALANCE OF SYSTEM

The balance of system (BOS) consists of a charge controller, inverter if used, and accessories such as blocking diodes, a lightning arrester, an electrical grounding system, and other electrical specialty items. Refer to Figs. 30.7 through 30.9 for a sense of how these components fit into a PV system. Although they are important to overall system performance and safety, a full description of these items is beyond the scope of this chapter. Refer to the references at the end of this chapter for a few of the many excellent resources that address these components.

30.8 DESIGN OF A STAND-ALONE PV SYSTEM

There is a fundamental difference in the procedures for array sizing and system arrangement between a stand-alone system and a

TABLE 30.1 Physical Characteristics of Typical 12-V[a] Batteries

Battery Type	Capacity in Amp-Hours	Dimensions of a 12-V Unit L × W × H in. (mm)	Weight lb (kg)
	(6/20/100-hr discharge rates)		
Deep-cycle	500/625/775	33 × 6.5 × 24 (838 × 165 × 609)	500 (227)
Lead–acid	675/840/1025	40 × 6.5 × 24 (1016 × 165 × 609)	700 (318)
	850/1050/1275	50 × 6.5 × 24 (1270 × 165 × 609)	800 (363)
	(20-h discharge rate)		
	850	40 × 8 × 24 (1016 × 203 × 609)	650 (295)
Sealed gel-cells	1050	40 × 9 × 24 (1016 × 229 × 609)	770 (349)
	1275	40 × 10 × 24 (1016 × 254 × 609)	930 (422)
	1500	40 × 12 × 24 (1016 × 305 × 609)	1100 (499)

[a]Use two units for a 24-V battery and four units for a 48-V battery.

grid-connected PV system. A stand-alone system must supply the entire electric load; there is no utility backup. Design decisions are primarily technical. A grid-connected system may supply part, or all, of the electric load. Design decisions are influenced by economics and owner intent, within the context of technical feasibility. These two procedures are addressed separately in this and the following section.

Figure 30.7 shows the essentials of a stand-alone PV system. Because building electricity demands rarely exactly match the output of a PV system, the system operates successfully by using a PV array to charge a battery, which then supplies the building load. Any occasional coincidence between load and PV production is incidental to the design process. The three factors that establish the system requirements are:

- The daily electricity usage
- The period of time for which the battery must supply the electric load without recharge
- The available insolation

The first factor is a function of building design. The second factor is a function of local weather conditions and would most often be chosen as the number of successive solid overcast or rainy days usually encountered. Designing for highly unusual weather results in a system that is oversized for normal (say, 95th percentile) weather patterns and, therefore, is essentially uneconomical. That scenario weighs heavily in favor of a hybrid system (see Fig. 30.8), which defeats, at least in part, the environmental benefits of the PV system.

The PV system design procedure is essentially straightforward and is as follows:

STEP 1. Determine the *average* daily energy usage in watt-hours.

STEP 2. Determine the maximum period for which the system battery must supply the entire electrical load.

STEP 3. Determine the required system battery capacity, which is equal to the daily load (Step 1) multiplied by the number of days that the battery must supply the load (Step 2). System losses are taken into account in this calculation. (In practice, this capacity can be reduced by switching off nonessential loads during unusually long sunless periods.)

STEP 4. Determine the preliminary size of the PV array. The array must supply all of the required electricity, that is, the facility's daily requirements (Step 1) plus all system losses. The preliminary array size is this capacity in terms of watt-hours. To determine the physical size of the array, the designer must determine the number of watt-hours produced per unit area of PV module. This involves knowledge of the site's solar radiation, the type and efficiency of the PV module used, mounting approach (stationary or tracking), and tilt angle (module angle measured from the horizontal). With these data in hand, the area of PV array required is simply the total load in watt-hours divided by the PV unit's energy production (perhaps obtained from PVWatts) in watt-hours per unit area.

STEP 5. Check that the array selected is sufficiently large to charge the battery capacity established in Step 3. Assuming, for instance, a 3-day period during which the battery must supply the entire load, about 3½ consecutive sunny days *at the same insolation* will be needed for full recharge (considering losses of approximately 20%). If the facility is to be used year-round and the PV array is sized on the basis of summer insolation, it is necessary to do a calculation for a winter month as well. Insolation data are usually available for both seasons, and average monthly insolation accounts for the appreciable energy available from cloudy skies as well as sunny skies. The result generally indicates a larger PV array requirement for winter months. In such cases, on purely economic grounds, the decision is often to use a small engine generator for battery-charging for winter use only. This is *not* the same as a hybrid system (Fig. 30.8), in which the generator is used year-round to pick up heavy AC loads. Some designers base the PV array size on *minimum* yearly (winter) insolation, reasoning that in other months any wasted overproduction from an array is the price paid for year-round operation without fossil fuels. Others use a median insolation figure, reasoning that power outages will be few and of short duration. Using summer insolation values will minimize the PV array size but probably will require inclusion of a small generator.

An illustrative example using the outlined design procedure should clarify the issues and calculations involved.

EXAMPLE 30.1 Design a stand-alone PV system for a 650-ft^2 (60-m^2) occupied-year-round, off-line cottage located near Prescott, Arizona. In addition to the usual appliances, an evaporative cooler is used during hot summer days. A PV array can be mounted on the south-facing sloping roof at any required angle. Determine the required battery and PV array sizes. State all assumptions.

SOLUTION

STEP 1. Determine the average electric energy consumption for the cottage. Although refrigerators that run on bottled gas are readily available, assume use of an electric refrigerator. Water heating is solar thermal, with a small gas booster heater. Cooking is with bottled gas.

24-V dc Appliances	Power Draw (W)	Daily Use (h)	Daily Energy Need (Wh)
Mid-sized refrigerator/ freezer	35	24	840
Small color TV	60	4	240
Evaporative cooler[a]	50	8	400
Stereo system	40	2	80
Ceiling fans[a] (3)	3 at 25	4	300
Radios	5	10	50
Incandescent lighting	50	8	400
		Daily use DC	2310 Wh

[a]Summer only.

120-V ac Appliances	Power Draw (W)	Daily Use (h)	Daily Energy Need (Wh)
Fluorescent lighting	80	10	800
Clothes washer	500	0.5	250
Vacuum cleaner	600	0.25	150
Kitchen appliances	400	1	400
Iron	1000	0.25	250
Miscellaneous	100	3	300
		Daily use[a] AC	2150 Wh

[a]Maximum coincident ac load.

Total daily energy usage:	
DC =	2310
AC = 2150 Wh × 1.15 (inverter loss)	2473
	4783 Wh
Ampere-hours = (4783 Wh/24 V) = 199, say 200 A-H	

STEP 2. Assume that investigation of local climate conditions indicates occasional periods throughout the year, but primarily in the winter, of 2–3 consecutive days of heavy overcast, clouds, and rain.

STEP 3. Sizing the system battery. Assume use of a deep-cycle flooded-cell lead battery with an appropriate charge controller. These batteries can supply about 80% of their rated ampere-hour capacity. Since the battery will be located indoors, but in an unheated room, it should be derated 15% for ambient temperature for a conservative design. Required battery size in ampere-hours equals:

$$\frac{3 \text{ days} \times 200 \text{ A-H daily load} \times 1.20 \text{ discharge factor}}{0.85 \text{ (temperature derating)}} = 850 \text{ A-H}$$

One type of 850-A-H, 24-V deep-cycle lead–acid battery (using two at 12-V units in series) measures approximately 40 in. long × 15 in. wide × 24 in. high (1020 mm × 380 mm × 610 mm) and weighs about 1500 lb (680 kg).

STEP 4. Sizing the PV array. Because the cottage will be occupied all year, and because the critical performance period is winter, when the sun is low, select a tilt of (latitude +15°) to maximize winter PV production. As the array is roof-mounted and will be relatively large, use a stationary rather than a tracking array. The array must supply the daily energy requirement of 4783 Wh or 4.8 kWh.

Referring to Fig. 30.12, which gives solar radiation data for the Prescott location, obtain the following data: average solar radiation for a PV array facing south at a tilt angle of latitude +15°:

January: 5.5 kWh/m^2/day; average monthly temperature 2.3°C (0.51 kWh/ft^2/day; 36°F)
June: 6.0 kWh/m^2/day; average monthly temperature 19.6°C (0.56 kWh/ft^2/day; 67°F)

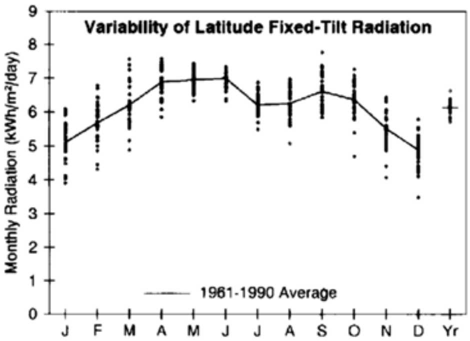
Figure 30.13 was drawn using the computer program PVFORM, developed at Sandia National Laboratories. It gives daily average PV array production in Wh/ft^2 as a function of monthly average temperature and monthly average solar radiation in kWh/m^2/day. Using the January and June radiation figures stated previously, obtain from Fig. 30.13:

January: 52 Wh/ft^2 of a PV array (560 Wh/m^2)
June: 53 Wh/ft^2 of a PV array (570 Wh/m^2)

The PV array output is essentially constant throughout the year (with radiation availability and ambient temperature effects offsetting), and no difficulty will be encountered in an "off" season. If the PV modules to be used have an efficiency greater than 10%, then the array output would be increased proportionately.

The required area of PV array, assuming 10% conversion efficiency, is:

PV area =
(4783 Wh/day required) / (52 Wh/day/ft^2 output)
= 91 ft^2 (8.5 m^2)



Prescott, AZ

WBAN NO. 23184

LATITUDE: 34.65° N
LONGITUDE: 112.43° W
ELEVATION: 1531 meters
MEAN PRESSURE: 847 millibars

STATION TYPE: Secondary

Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.1	3.9	5.1	6.6	7.5	8.0	6.9	6.3	5.7	4.6	3.4	2.8	5.3
	Min/Max	2.6/3.5	3.2/4.5	4.2/6.1	5.7/7.1	6.8/8.0	7.2/8.5	6.1/7.7	5.1/7.0	5.1/6.7	3.6/5.2	2.8/3.9	2.2/3.2	5.1/5.7
Latitude -15	Average	4.4	5.1	5.9	7.0	7.5	7.7	6.7	6.5	6.5	5.8	4.8	4.1	6.0
	Min/Max	3.5/5.1	4.0/6.0	4.7/7.2	6.0/7.7	6.8/8.0	6.9/8.1	5.9/7.5	5.3/7.2	5.7/7.6	4.4/6.6	3.7/5.5	3.0/4.8	5.6/6.5
Latitude	Average	5.1	5.7	6.2	6.9	7.0	7.0	6.2	6.3	6.6	6.4	5.5	4.9	6.1
	Min/Max	3.9/6.1	4.3/6.8	4.9/7.6	5.8/7.6	6.3/7.4	6.3/7.3	5.5/6.9	5.1/7.0	5.8/7.8	4.7/7.3	4.1/6.4	3.5/5.8	5.7/6.6
Latitude +15	Average	5.5	5.9	6.1	6.4	6.1	6.0	5.4	5.7	6.4	6.5	5.9	5.4	5.9
	Min/Max	4.2/6.6	4.4/7.1	4.8/7.5	5.4/7.1	5.6/6.5	5.4/6.3	4.8/5.9	4.6/6.3	5.6/7.5	4.7/7.5	4.3/6.9	3.7/6.4	5.5/6.4
90	Average	5.0	4.9	4.3	3.5	2.6	2.3	2.3	2.9	4.0	5.0	5.2	5.0	3.9
	Min/Max	3.8/6.1	3.6/5.9	3.4/5.2	3.0/3.8	2.5/2.8	2.2/2.3	2.1/2.4	2.4/3.1	3.6/4.7	3.6/5.8	3.6/6.2	3.4/6.0	3.5/4.2

Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m²/day), Uncertainty ±9%

Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	4.8	5.9	7.4	9.4	10.6	11.3	9.3	8.8	8.4	7.1	5.4	4.4	7.7
	Min/Max	3.7/5.7	4.4/7.2	5.7/9.5	7.9/10.6	9.4/11.5	9.9/12.0	7.9/10.8	7.0/10.1	7.1/10.2	5.0/8.2	4.0/6.3	3.2/5.2	7.1/8.4
Latitude -15	Average	5.7	6.8	8.1	9.8	10.6	11.2	9.3	9.0	9.0	8.0	6.3	5.4	8.3
	Min/Max	4.3/6.9	5.0/8.3	6.2/10.3	8.2/11.0	9.4/11.6	9.8/11.9	7.8/10.7	7.1/10.4	7.6/10.9	5.6/9.3	4.6/7.5	3.8/6.4	7.5/9.0
Latitude	Average	6.3	7.2	8.3	9.8	10.3	10.7	8.9	8.8	9.1	8.4	6.9	6.0	8.4
	Min/Max	4.7/7.6	5.3/8.8	6.3/10.6	8.1/11.0	9.2/11.3	9.4/11.4	7.6/10.4	7.0/10.2	7.7/11.1	5.8/9.8	4.9/8.2	4.1/7.2	7.6/9.2
Latitude +15	Average	6.6	7.4	8.2	9.4	9.7	10.1	8.4	8.4	8.9	8.5	7.2	6.3	8.3
	Min/Max	4.9/8.1	5.3/9.1	6.2/10.6	7.7/10.6	8.6/10.6	8.8/10.7	7.1/9.7	6.7/9.8	7.5/10.9	5.8/9.9	5.1/8.6	4.3/7.6	7.5/9.0

Average Climatic Conditions

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°C)	2.3	3.9	5.9	9.6	14.2	19.6	22.8	21.3	18.1	12.6	6.7	2.6	11.7
Daily Minimum Temp	-5.6	-4.4	-2.2	0.8	5.1	9.9	14.4	13.2	9.3	3.4	-1.9	-5.4	3.1
Daily Maximum Temp	10.2	12.2	14.1	18.3	23.3	29.2	31.2	29.4	26.7	21.8	15.3	10.6	20.2
Record Minimum Temp	-18.3	-18.3	-13.9	-6.1	-3.3	2.2	8.3	4.4	1.1	-7.2	-13.3	-22.8	-22.8
Record Maximum Temp	23.3	25.0	27.2	30.6	35.0	39.4	38.9	37.2	35.0	32.2	26.1	21.1	39.4
HDD, Base 18.3°C	496	403	384	262	138	32	0	0	41	182	350	489	2775
CDD, Base 18.3°C	0	0	0	0	11	68	139	96	32	4	0	0	351
Relative Humidity (%)	59	53	49	38	33	27	44	51	47	46	51	59	47
Wind Speed (m/s)	3.1	3.5	4.1	4.2	4.3	4.1	3.5	3.1	3.4	3.3	3.3	3.0	3.6

Fig. 30.12 *Solar radiation data for Prescott, Arizona. (From* Solar Radiation Data Manual*, National Renewable Energy Laboratory, 1994.)*

STEP 5. Because the solar radiation in Prescott, Arizona, is essentially identical for summer and winter, PV production in 3 to 3½ clear days will fully recharge the battery, as explained previously. However, in sizing PV systems, the need to provide charge to discharged batteries while simultaneously providing power to building loads should be considered. A system sized just large enough to meet all loads under design conditions will generally not have sufficient output to recharge depleted batteries.

Summary. The suggested PV system consists of approximately 90 ft^2 (8.4 m^2) of PV collector, an 850-A-H, 24-V battery, and a 1500-W inverter to handle the initial load plus the anticipated addition of small AC appliances. The summer-only DC cooling loads will likely be offset in winter by additional use of lighting and television and other in-cottage activities.

Additional Considerations. Using accurate radiation and weather data for a site is necessary for the design of an efficient and workable system. Unfortunately, accurate radiation data, particularly for tilted surfaces, are not always available, and tilted-surface data are not easily derived from horizontal-surface or normal-to-the-sun data. PV installations are frequently planned for sites outside of large cities, and it is usually for these areas that a paucity of

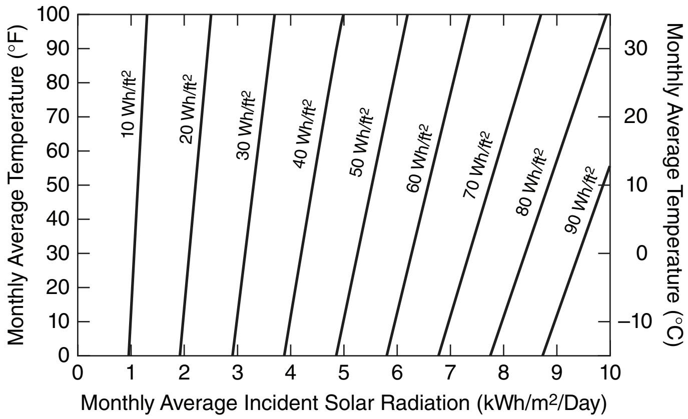


Fig. 30.13 *Daily average PV array production, Wh/ft^2, as a function of monthly average temperature and incident solar radiation. Production was calculated using PVFORM for a 10% efficient solar cell array at 77°F (25°C) ambient temperature. (Reprinted with permission from "Design for PV," Association of Collegiate Schools of Architecture.)*

data exists. In such instances, data for nearby areas can be used but must be applied judiciously, as insolation conditions can vary sharply within a relatively small geographic area. ■

30.9 DESIGN OF A GRID-CONNECTED PV SYSTEM

The design procedure for an interactive system (with feedback into the utility grid; see Fig. 30.9) differs from the typical stand-alone system design procedure described in Section 30.8. The principal differences are:

- The loads in an interactive system are all AC rather than a mix of AC and DC because the building is fed from the utility line or from the PV array DC-to-AC inverter; DC is not available to the loads.
- The existence of a PV system has no bearing on the choice of fuel for appliances. Therefore, for instance, whether to use gas or electric cooking is a matter of fuel availability, costs, and owner preferences.
- Loads are generally heavier in interactive systems because one cannot run out of electric power, as with a stand-alone system. As a result, an all-electric house or a heavily automated house can be a candidate for a PV system as much as any other building.
- Load data can be obtained for a specific design or from general utility-supplied data similar to those shown in Figs. 30.14 and 30.15.
- Inasmuch as no battery and associated control equipment is used, space allocation in the structure for PV-related equipment is small, and system maintenance is minimal. Also, system life is equivalent to PV array life. Design note: Some areas in North America have recently been hit with uncharacteristic ice storms that have caused unexpected and relatively lengthy power outages. Some owners with grid-connected PV systems in these areas have added a small battery to their systems to meet their essential needs (lights, heating, computer use) through such outages.

Assuming a net-metering arrangement, there is no advantage to coincidence of building electrical loads and peak PV production. This is emphatically not the case where PV production buyback is based upon avoided costs. In such situations, careful scrutiny of the utility's rate schedule may yield cost-saving opportunities in matching loads to lower-rate time periods. For nonresidential buildings, careful consideration of future electric loads should be reflected in architectural planning for future (larger) PV arrays. In this connection, the possibility of using distributed arrays, as in Fig. 30.10, should be studied.

The general design procedure for a grid-connected PV system is as follows:

STEP 1. Establish with the power company the metering arrangement to be used, both physical and financial. The utility can also generally supply

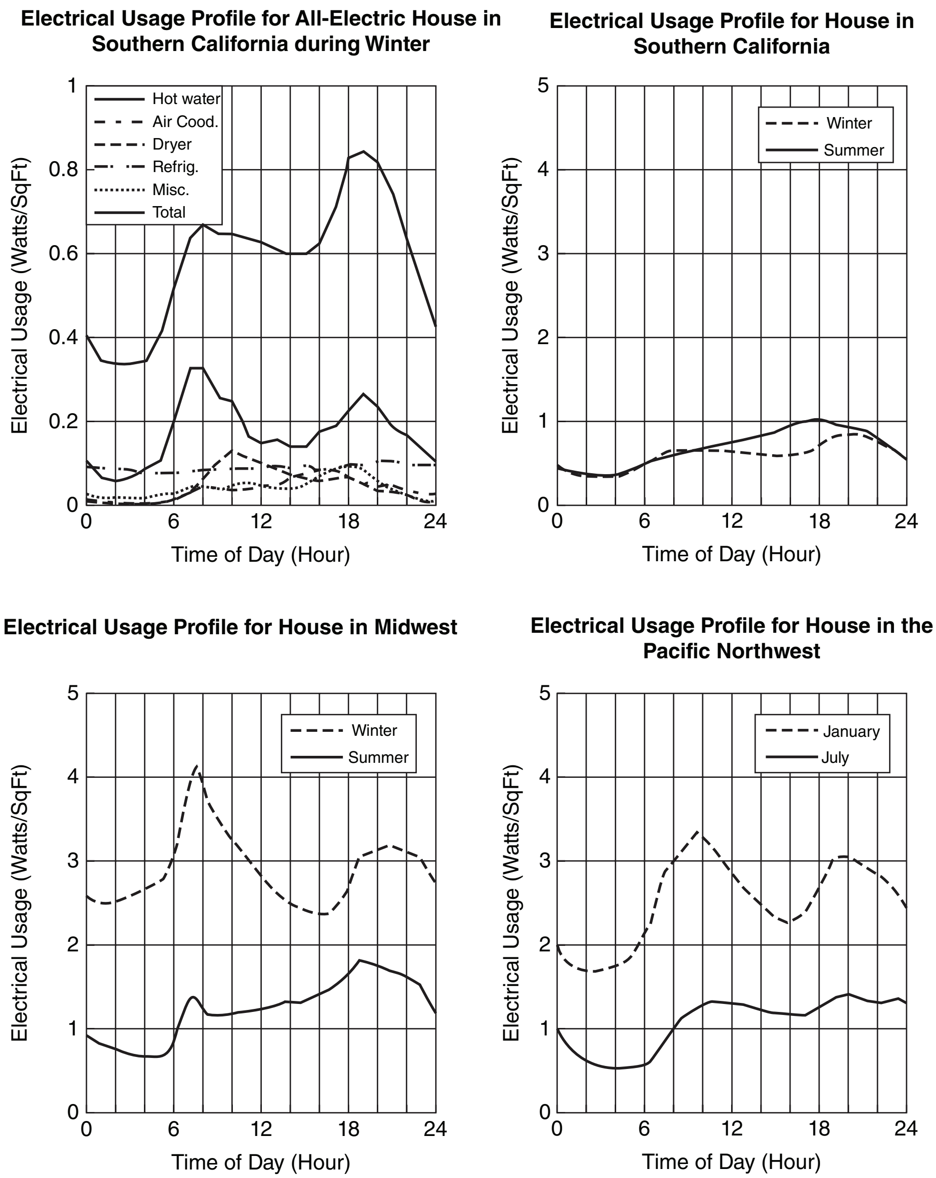


Fig. 30.14 *Typical residential electricity usage profiles based on a 1500-ft² (140-m²) house. (Reprinted with permission from "Design for PV," Association of Collegiate Schools of Architecture.)*

reliable data on solar radiation, load patterns, PV array sizing and tracking feasibility, and other relevant design data.

STEP 2. Using a detailed cost analysis, determine the optimum size of the PV array in today's market. Although this analysis will involve technical data, the decision on an optimum size is essentially economic—trading utility cost savings against additional first costs for the PV system within a feasibility window established by the owner. This economic feasibility window will likely be influenced

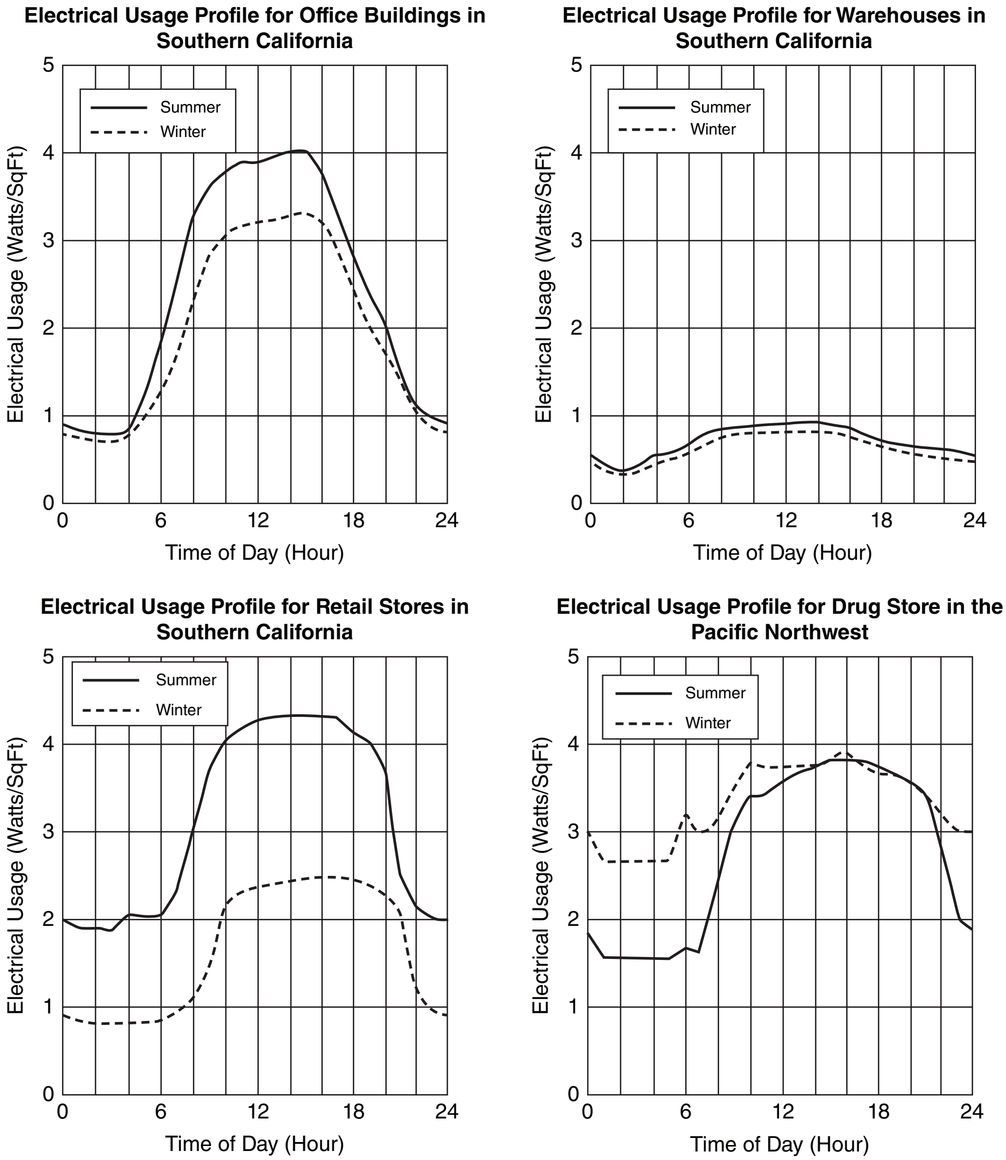


Fig. 30.15 *Typical electric load profiles for nonresidential U.S. buildings. (Reprinted with permission from "Design for PV," Association of Collegiate Schools of Architecture.)*

by qualitative factors such as a desire to reduce dependence on the "grid," a desire to be more environmentally friendly, or a desire to use a PV system to obtain green building certification points. Sensitivity analysis can be incorporated into the economic analysis to suggest ranges of reasonable system sizes given estimated changes in economic variables such as utility rates, tax credits, or future PV array costs.

STEP 3. Using specific data or generalized information similar to that given in Figs. 30.14 and 30.15, determine the required performance characteristics and physical size of the PV array established in step 2.

30.10 CODES AND STANDARDS

PV installations are electrical systems and therefore fall under the purview of NFPA 70, the *National Electrical Code* (*NEC*), published by the National Fire Protection Association. Article 690 of the *NEC*—"Solar Photovoltaic Systems"—is devoted specifically to such systems. Its requirements, plus those of applicable articles in the remainder of the *NEC*, must be observed in all areas where the *NEC* is mandated by local jurisdiction. In addition, for grid-connected systems, the specific requirements of the local utility must be followed, all equipment approved by them, and the final installation subject to their inspection.

Other codes and standards that contain important information and may be applicable if required by local authorities include (IEC = International Electrotechnical Commission; IEEE = Institute of Electrical and Electronics Engineers; UL = Underwriters Laboratories):

IEC 61194 Ed. 1.0 b:1992: *Characteristic Parameters of Stand-Alone Photovoltaic (PV) Systems* (withdrawn, but available for purchase)

IEC 61727 Ed. 2.0:2004: *Photovoltaic (PV) Systems—Characteristics of the Utility Interface*

IEC 61215 ed. 2.0:2005: *Crystalline Silicon Terrestrial Photovoltaic (PV) Modules—Design Qualification and Type Approval*

IEC 61173 ed. 1.0:1992: *Overvoltage Protection for Photovoltaic (PV) Power Generating Systems* (withdrawn, but available for purchase)

IEC 61277 ed. 1.0:1995: *Terrestrial Photovoltaic (PV) Power Generating Systems—General and Guide* (withdrawn, but available for purchase)

IEC 61702 ed. 1.0:1995: *Rating of Direct Coupled Photovoltaic (PV) Pumping Systems*

IEEE 1013-2007, *Recommended Practice for Sizing Lead–Acid Batteries for Stand-Alone Photovoltaic (PV) Systems*

IEEE 937-2007, *Recommended Practice for Installation and Maintenance of Lead–Acid Batteries for Photovoltaic (PV) Systems*

UL 1703-2002, *Standard for Flat-Plate Photovoltaic Modules and Panels*

UL 1741-2010, *Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources*

As with most standards, these are regularly updated; verification of the most current version is advised.

30.11 PV INSTALLATIONS

PV power appears to be one of the dominant trends of the future. PV and buildings are too logical a connection to not develop into the norm. Even today, with unfavorable economics, numerous notable examples of PV installations exist. Several interesting examples are presented here.

Example 1: PV integrated with solar hot water collectors (Fig. 30.16). This is an interesting application that matches resource with need and obviates the need for storage of the PV system's energy production. The PV output drives a pump that circulates solar-heated water. The pump operates only when there is enough solar radiation to heat the water, which means there is also enough radiation to drive the pump via the PV module. No batteries or grid backup are required.

Example 2: Many parking lots feature canopies of photovoltaic arrays that also serve as a shading source. The Springs Preserve parking lot (Fig. 30.17) in Las Vegas, Nevada, uses small, two-sided, single-axis tracking modules to provide 409 kW of peak capacity.

Example 3: Photovoltaics at the Woods Hole Research Center (Fig. 30.18), Falmouth, Massachusetts. This green building features a substantial PV installation. The system is a net-metering arrangement (as described earlier). For further information, see the case study on this project presented in Chapter 1.

Example 4: PV on a solar racer (Fig. 30.19), Australia, 1983. An early example of TIPV (transportation-integrated photovoltaics)? The lessons presented by this example actually apply well to buildings—reduce the load and optimize the collectors.

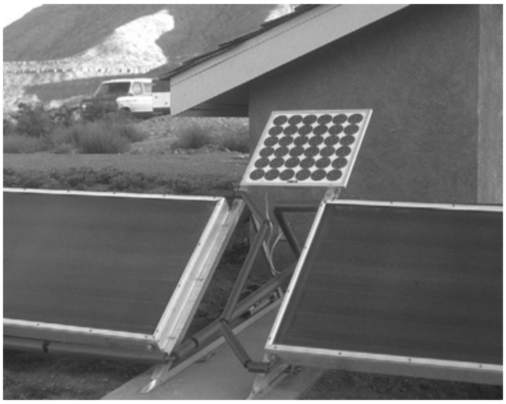


Fig. 30.16 *Synergistic PV application—pumping hot water produced by solar collectors for a residence in the Southwestern United States. (© Walter Grondzik; all rights reserved.)*

Fig. 30.17 *Six, single-axis photovoltaic arrays at the Springs Preserve in Las Vegas, Nevada, are positioned over highly reflective fabric panels. (© Alison Kwok; all rights reserved.)*

(*a*) (*b*)

Fig. 30.18 *PV at the Woods Hole Research Center, Falmouth, Massachusetts. (a) Low-slope PV array on the roof of the building. (b) An inverter (one of several) and a disconnect switch are also located on the roof. (© Walter Grondzik; all rights reserved.)*

Fig. 30.19 *The PV car, a solar racer, after crossing Australia (not a minor feat). (© Walter Grondzik; all rights reserved.)*

30.12 CASE STUDY—PV

Lillis Business Complex, the University of Oregon

Project Basics

- Location: Eugene, Oregon, USA
- Latitude: 44.1°N; longitude: 123.2°W; elevation: 425 ft (130 m) above sea level
- Heating degree days: 4546 base 65°F (2528 base 18.3°C); cooling degree days: 300 base 65°F (167 base 18.3°C); annual precipitation: 43 in. (1092 mm); cloud cover: 75 clear days a year, 82 partly cloudy, and 209 cloudy
- Building type: Institutional—classrooms, offices, common areas
- Building area: 196,500 ft^2 (18,255 m^2); four occupied stories
- Completed October 2003
- Client: University of Oregon
- Design team: SRG Partnership with Solar Design Associates (PV) and consultants

Background. The Lillis Business Complex is an academic facility situated adjacent to a major circulation axis on the University of Oregon campus in Eugene. The building has the size, character, and location to serve as a teaching tool for thousands of students who walk by on any given day. North American universities as a rule (with notable exceptions) have not been in the forefront of the renewable energy movement. This project is one of the exceptions.

Context. The Lillis Business Complex is an example of what can happen when various positive forces come into alignment on a project. In this case, an aware client seeking innovation partnered with a local utility promoting the use of alternative energy sources on a campus with an active Energy Studies in Buildings Laboratory (ESBL). The resulting

Fig. 30.20 *South façade of the Lillis Business Complex, Eugene, Oregon. The atrium glazing incorporates PV cells in this façade example of building-integrated PVs. (© Karen Tse; used with permission.)*

Fig. 30.21 *Glazing panel on the Lillis Business Complex showing embedded PV cells. The glazing essentially acts as a power plant while still providing for views and daylighting. (© Alison Kwok; all rights reserved.)*

Fig. 30.22 *Close-up view of an embedded polycrystalline PV cell at the Lillis Business Complex with interconnecting conductor strips. (© Alison Kwok; all rights reserved.)*

synergy enabled this project to evolve into its final form without too much compromising of objectives. Utility support for the PV system was critical to its inclusion in the project; the utility will buy PV power output at $0.25 per kWh under a 10-year agreement.

Design Intent. The Lillis Business Complex was intended to be an example of innovation, particularly with respect to energy and the environment. An aggressive energy goal of 40% beyond the minimum efficiency required by code set a challenging benchmark for many design decisions. Other green design features flowed from the intent to achieve Leadership in Energy and Environmental Design (LEED) certification for the project.

Design Criteria and Validation. A desire for LEED certification provided the general criteria for the green features of the building (see Appendix G.2). The specific "40% better" energy benchmark provided the criterion for energy performance. Extensive modeling and analysis of concepts and systems were conducted by various consultants (including ESBL) during the course of the design process as a means of verifying design approaches and implementation methods. The building was commissioned.

Key Design Features

- The third-largest PV array in Oregon, with a peak capacity of about 45 kW of electricity
- A green roof, the first application of this design approach at the university
- Extensive use of daylighting, involving lightshelves and solar shading devices
- Efficient electric lighting using dimmable fluorescent lamps with electronic ballasts and daylight sensor controls
- "Smart plugs" that are wired to occupancy sensors to turn off devices in unoccupied offices
- An integrated natural ventilation system to accommodate outdoor air needs (for acceptable indoor air quality [IAQ]), to cool the space and people, and to cool the thermal mass; ceiling fans augment the ventilation system
- Thermal mass to provide storage capacity for ventilation cooling and help the building heat up more slowly in summer and cool more slowly in winter

Post-Occupancy Validation Methods and Performance Data. The total PV system output is approximately 45 kW peak (DC). There are four distinct PV elements in the building. These include the PV cells integrated into the south-facing glass curtain wall

Fig. 30.23 *View from the atrium of the Lillis Business Complex; the integrated PV cells provide partial shading and a lively lighting pattern. (© Alison Kwok; all rights reserved.)*

Fig. 30.24 *Fisheye view of the Lillis Business Complex atrium. The south-facing panels of the rectangular skylights also contain embedded PV cells. (© Alison Kwok; all rights reserved.)*

at the entry, which produce about 6 kW (DC), and 2.7 kW (DC) of PV cells incorporated into skylights above the atrium. These two PV applications are good examples of BIPV. The PV cells are integrated into the glazing units such that these units are also the PV modules. In addition, another 6 kW (DC) of PV units are installed on sloping penthouse roof panels, and another 30 kW (DC) installed horizontally. Each element of the PV system is connected to separate inverter systems to maximize system output.

FOR FURTHER INFORMATION

Brown, G. Z., et al. 2004. "A Lesson in Green." *Solar Today,* Vol. 18, No. 2.

References and Resources

Various standards from IEC, IEEE, and UL dealing with PV systems are presented in Section 30.10.

ACSA. 1993. *Design for PV*. Association of Collegiate Schools of Architecture. Washington, DC.

CIBSE. 2000. *Understanding Building Integrated Photovoltaics*. The Chartered Institute of Building Service Engineers. London, UK.

Markvart, T. (ed.). 2000. *Solar Electricity*, 2nd ed. John Wiley & Sons. New York.

Messenger, R. and J. Ventre. 2003. *Photovoltaic Systems Engineering*, 2nd ed. CRC Press. Boca Raton, FL.

National Renewable Energy Laboratory. Accessed 2013. PVWatts: A Performance Calculator for Grid-Connected PV Systems. http://rredc.nrel.gov/solar/calculators/pvwatts/version1/

Sandia National Laboratories. 2004. Photovoltaic Systems Research & Development: http://www.sandia.gov/pv/

Strong, S. 1994. *The Solar Electric House: Energy for the Environmentally-Responsive, Energy-Independent Home*. Sustainability Press. Still River, MA.

Strong, Steven. 2011. "Building Integrated Photovoltaics (BIPV)." Whole Building Design Guide. National Institute of Building Sciences. http://www.wbdg.org/resources/bipv.php

PART VIII

SIGNAL SYSTEMS

Modern buildings, from the simplest residence to the most complex industrial facility, depend extensively upon electrical, signal, alarm, control, and communication systems in their day-to-day functions. The systems discussed in this part of the book deal with security, music/sound, intercom, clock and program, paging, and building automation. (Fire and smoke detection and alarms are covered in Chapter 25.) Individual, single-purpose systems are discussed from the point of view of a user—that is, emphasizing system application rather than design.

Operating principles are presented, and application issues are related to available equipment. Although equipment is constantly being improved, operating and application principles remain substantially constant, thereby permitting the designer to readily adapt newly available hardware to existing system arrangements.

In terms of building automation, which is essentially a complex control system with sophisticated hardware, the discussion is limited to system architecture and application issues. A discussion of hardware, protocols, and software would be too detailed and would necessarily lag behind the times in a field that doubles its computing power, and therefore its control capability, roughly every 18 months.

CHAPTER 31

Signal Systems

31.1 INTRODUCTION

NO AREA OF EQUIPMENT DESIGN AND APPLICATION in buildings has seen such rapid and sustained changes as that of signal equipment. Signal equipment encompasses all communication and control equipment, the function of which is to assist in ensuring proper building operation. Included are: surveillance equipment such as that for fire and access control; audio and visual communication equipment such as telephone, intercom, and television (both public and closed-circuit); and timing devices such as clock and program equipment and all types of time-based controls. Specifically excepted is the area of occupant data processing, which is not within the province of the building designer, except for equipment space allocations.

Clock and program equipment, which once was limited to schools and some industrial facilities, is now incorporated into building mechanical equipment control systems. Closed-circuit TV, which once was limited to classroom and college use, is now commonplace in mercantile area surveillance systems. The hundreds of signals generated throughout a large facility are logged, channeled, and controlled by means of specially programmed computers and microprocessors. Signal systems that once were separate and distinct are now frequently combined and serve multiple purposes.

A detailed study of the design and application of such diverse equipment is beyond the scope of this book or, for that matter, of any single book. This chapter, however, discusses the basic operation of the various systems, some of the equipment available, its application to different types of facilities, and the impact of these systems on building spaces. The types of facilities considered are single and multiple residences, schools, stores, office buildings, and industrial facilities. Hospitals and laboratories are combinations of these types, but they are too highly specialized to be discussed here.

31.2 PRINCIPLES OF INTRUSION DETECTION

To understand the design of intrusion detection systems, it is necessary first to understand the characteristics of the commonly available intrusion detectors (sensors) on which these systems are based. Once an intrusion event has been detected by a sensor, the signal must be processed and appropriate measures taken. This may include sounding loud alarms, turning on lights, and/or sending signals to central proprietary or private surveillance services or police.

(a) Sensors with Normally Open (NO) Contacts

These devices are no longer used in any reputable system because the circuits are unsupervised.

As a result, a defective circuit does not indicate trouble, and the system is thereby rendered ineffective.

(b) Simple Normally Closed (NC) Contact Sensors

These come in a variety of designs, the most common of which are magnetic contacts for doors and windows, spring-loaded plunger contacts for doors and windows, window foil, and pressure/tension devices. They operate to transmit an alarm signal, as noted previously. Used in closed, supervised circuits, they provide a trouble signal when the sensors or circuits are damaged.

(c) Mechanical Motion Detectors

Where window foil or fixed contacts are impractical, a mechanical motion detector can be used. This device is basically a spring-mounted contact suspended inside a second contact surface. Any appreciable motion of the surface on which the device is placed causes the contacts to momentarily "make," turning on an alarm. These devices are very sensitive and can be activated by sonic booms, wind, and even a heavy truck passing by. For this reason, most units are provided with sensitivity adjustment.

(d) Photoelectric Devices

These devices operate on the simple principle of beam interruption. When the beam is received, a contact in the receiver is closed. Interruption of the beam causes the contact to open, setting off the alarm. Older devices of this design use a visible beam (light) and rely for concealment on the fact that light is seen only when reflected from an intervening object. This is quite effective indoors, but outdoors, dust, insects, birds, and so on can show the location of the beam, permitting it to be circumvented. Birds and small animals can set it off, too. Dispersion of light also limits the throw of the devices when used outdoors. Modern units use lasers or infrared (IR) beams, which are less easily detected and can be arranged to distinguish between intruders and other disturbances. These latter devices have a longer effective range for exterior use. When a laser beam is used, the signal can be picked up, amplified, and retransmitted in a different direction, thus establishing a perimeter security "fence" from a single source.

(e) Passive Infrared (PIR) "Presence" Detector

This device (Fig. 31.1*a*) acts on the principle that all objects emit IR radiation, or heat. The amount radiated depends primarily on the object's temperature and secondarily on its material, color, and texture. The PIR sensor uses a lens or mirror that focuses on a small area and concentrates the IR radiation collected from the conic volume of space that falls between the device and the target area of the IR sensor, forming, in effect, a conical beam of coverage called a *zone*. IR radiation in an area that is undisturbed (not necessarily unoccupied) changes very slowly (because object temperatures change very slowly). As a result, any rapid change in the IR reading of a zone indicates an object entering (or leaving) the space, and this triggers an alarm. These detectors can be used as occupancy sensors to turn off lights when occupants leave a space.

The ability to focus on a particular area is utilized to cover areas both horizontally and vertically by the simple expedient of using multiple lenses or mirrors to create multiple zones that cover any desired volume of space (see Fig. 16.26). Also, inasmuch as the IR detector is not intrinsically sensitive to motion, but only to heat, it is usable where motion in the monitored area is unavoidable. The principal disadvantage of PIR detectors is that rapid temperature changes caused by direct solar insolation, a cold breeze, a heater turning on, and the like, can cause false alarms. PIR detectors are applied as sensitive motion detectors by using a multibeam (zone) unit. Motion is detected as changes in the IR radiation of adjacent zones or in the radiation of a zone (target) with respect to the background, both of which characterize motion.

(f) Motion Detectors

These devices (Fig. 31.1*b*), which operate at either microwave or ultrasonic frequencies,

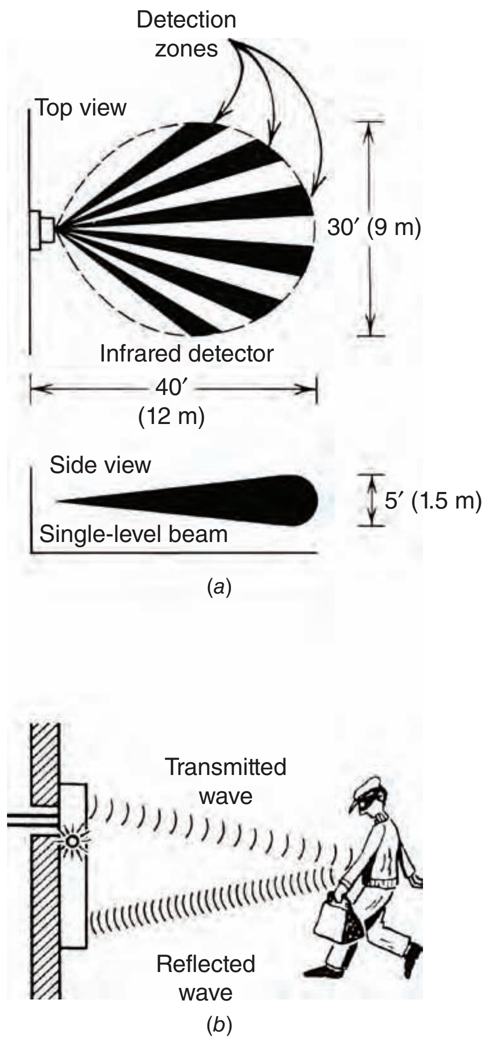


Fig. 31.1 *(a) Passive infrared detectors give generally a 30 × 40 ft (9 m by 12.2 m) oval protective zone, starting as a narrow beam and widening with distance. Focusability permits exact coverage of any area in a space. Units are also readily available with multiple vertical sensitivity stacked beams that give the same type of high-level interbeam vertical sensitivity as is available from multiple horizontal beams (zones). (b) Motion detectors depend upon the Doppler effect. They detect changes in the frequency of a signal reflected from a moving object. Sensitivity is highest when relative motion is greatest, that is, when the intruder is moving directly toward (or away from) the detector.*

detect motion in the protected area by the Doppler effect. (This is the effect that changes the perceived sound of a car horn or train whistle as the vehicle passes.) Any moving body changes the received frequency of the signal it reflects, and an alarm sounds. However, because the Doppler effect depends on relative motion between the source and the moving body, an intruder moving laterally may go undetected if sensitivity has been reduced to avoid false alarms. Therefore, units should be located so that the path of an intruder is as nearly as possible directly toward or away from the detector. Ultrasonic units are cheaper than microwave units but can be disturbed by strong air turbulence and very loud noises. Microwave units are undisturbed by air or noise, but because they (like ordinary TV signals) penetrate solids, they can be affected by motion outside the protected area.

(g) Acoustic Detectors

These units alarm when the sound pressure level exceeds a preset maximum. Alternatively, they can be arranged to respond to a particular range of frequencies corresponding to the sound of breaking glass, forced entry, or whatever is desired. Although applied principally in security systems, they can also be used as occupancy sensors for control of lighting.

A selection of the devices described in this section is shown in Fig. 31.2.

As with fire detectors, a balance must be struck between the sensitivity of detectors and the nuisance of false alarms, as, unfortunately, increasing the former increases the latter as well. One very effective method of reducing nuisance alarms is to use multiple detectors with different technologies that, in effect, verify each other. Thus, as with occupancy detectors, units are available that combine PIR and ultrasonic detectors in a single housing. Such a unit does not transmit an alarm until both detectors indicate intrusion. This dual technique is applicable to area and perimeter protection as well as portal surveillance.

The previous discussion and that immediately following refer only to intrusion detection (i.e., indication of a human presence where it should not be). *Access control*, which is another area of security design, deals with controlled entry to an area. It is generally more complex than intrusion control, and uses different technologies and a different philosophy of design (see Section 31.24).

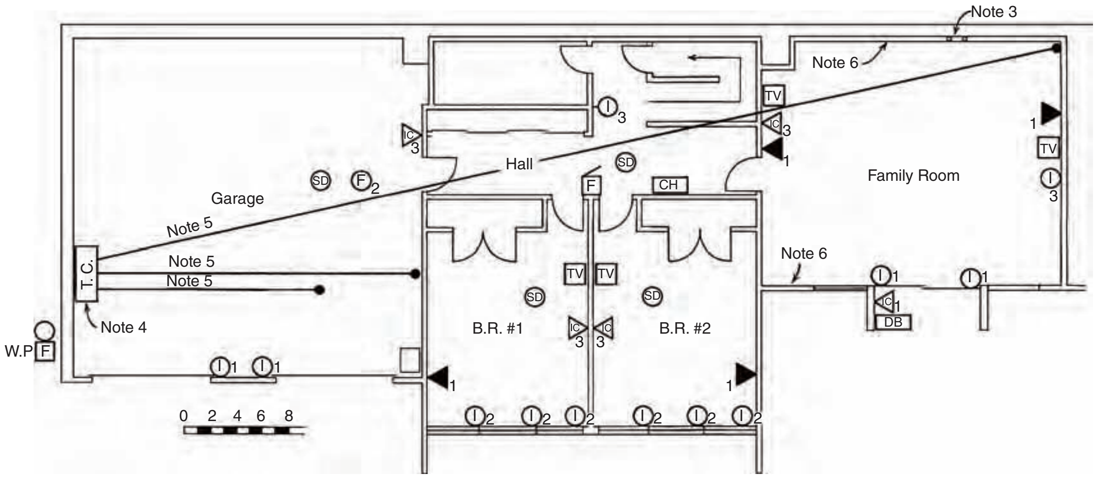
Fig. 31.2 *Typical intrusion detection equipment: (1) Passive infrared detector. Maximum sensitivity is a 4F° (2C°) differential between target and background and a target motion of 2½ in./s (64 mm/s). The unit is approximately 6 in. (150 mm) deep. These detectors are available with different coverage patterns and a maximum coverage of 2000 ft^2 (185 m^2). (2) High-sensitivity, multizone, wide-angle passive infrared detector gives coverage of 17 zones horizontally and vertically. (3) Ultrasonic detectors arranged to give broad coverage of approximately 200 × 50 ft (61 by 15 m). Each unit is 11 × 5½ × 3½ in. (280 × 140 × 90 mm). (4) High-sensitivity, balanced signal type of ultrasonic detector differentiates between an intrusion signal and random environmental signals, thus reducing false alarms. (5) Unobtrusive, button-type ultrasonic sensor intended for ceiling mounting. (6–8) System control panel, annunciator, and mechanical alarm interface units. (Photos courtesy of Sentrol, an SLC Technologies Company.)*

PRIVATE RESIDENTIAL SYSTEMS

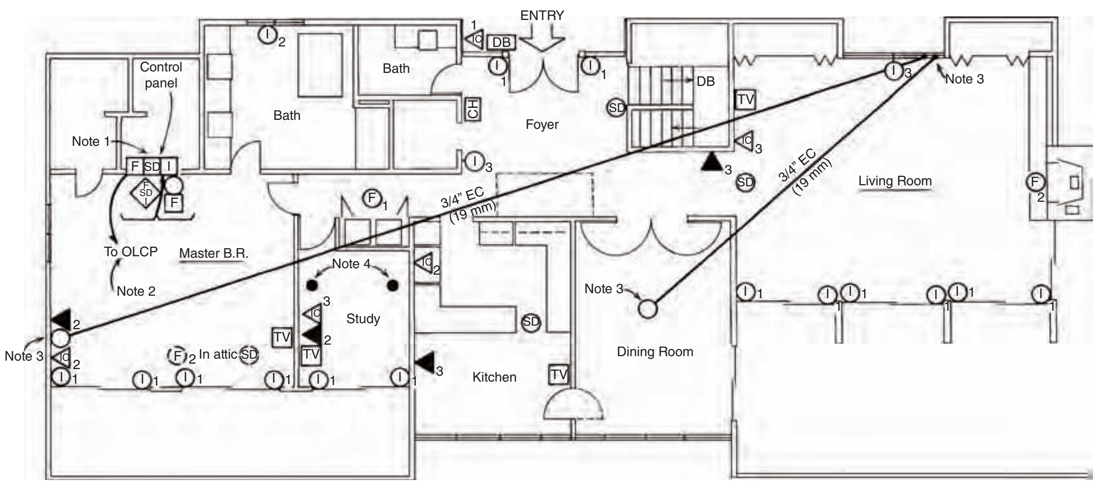
31.3 GENERAL INFORMATION

Modern private residences utilize a variety of signal devices that greatly enhance their functional value. Indeed, automation in residences, which includes control of and by a host of signal systems, is today a key factor in perceived property value. Figure 31.3 shows a conventional, nonautomated residential plan providing what would be considered *minimally* adequate sound and signal equipment.

In general, all signal systems require a signal source; equipment to process the signal, including transmitting it; and finally, a means of indicating the signal, whether audibly, visually, or on a permanent hard copy. A complex system still falls into this threefold category except that the individual items of equipment and their functions become more sophisticated. Most designers are familiar with the sophisticated automated systems available in the residential market that handle security, fire alarm, time functions, lighting, and so on. They function on dedicated wiring, control bus, or power line carrier (PLC) signals (high-frequency signals impressed on electric power wiring). To focus on the basics,



(*a*)

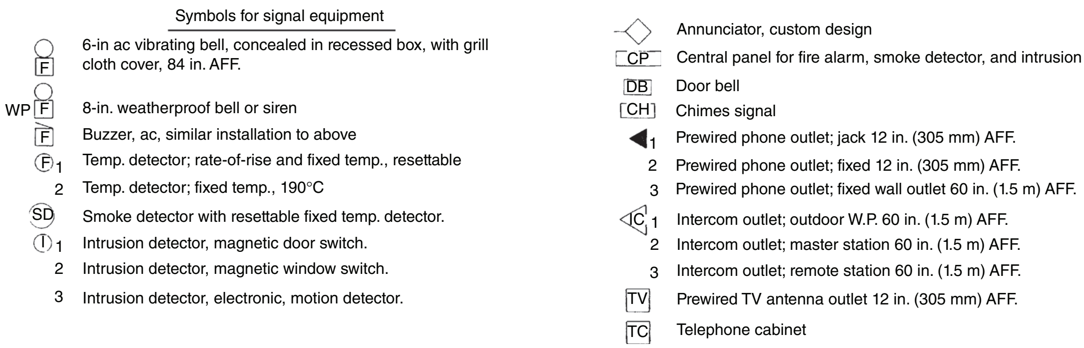


(*b*)

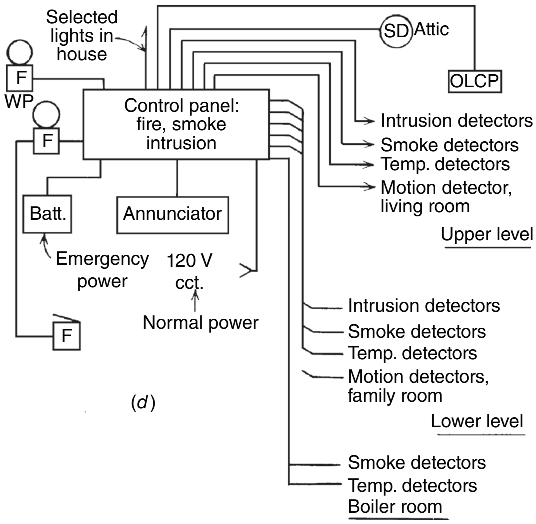
Notes:

1. *The fire detection, smoke detection, and intrusion alarm devices all operate from a single control panel; see (d). The alarm bell is common. The annunciator indicates the device that operated and its location.*
2. *The connection between the signal control panel and OLCP (outside lighting control panel) activates all outside light fixtures when a signal device trips. Selected light fixtures inside the house can also be connected to turn on. See riser diagram (d).*
3. *Two ¾-in. (20-mm) empty plastic conduits, extending from 4-in. (100-mm) boxes in living room wall down to family room and terminating in 4-in. (100-mm) flush boxes. Boxes to be 18 in. (460 mm) above the finished floor (AFF) and fitted with blank covers. Also, extend a ¾-in. (20-mm) empty plastic conduit from one 4-in. (100-mm) box in living room to 12-in. (300-mm) speaker backbox recessed in dining room ceiling. Locate in the field. From the second 4-in. (100-mm) box in living room extend a ¾-in. (20-mm) empty plastic conduit to an empty 4-in. (100-mm) box in the master bedroom, 18 in. (460 mm) AFF. Finish with blank cover.*
4. *Coordinate the location and size of the telephone entrance service cabinet (or box) with the phone company. Extend a ¾-in. (20-mm) empty plastic conduit from the telephone entrance cabinet to each of the signal raceways in the study. Extend one 1¼-in. (32-mm) or two ¾-in. (20-mm) empty plastic conduits from the cabinet to the empty signal raceway around the perimeter of the family room.*
5. *Provide a ¾-in. (20-mm) EC through the wall and capped at both ends, for entry of cables from an exterior satellite dish. Coordinate location with TV/CATV/satellite dish contractor.*
6. *Boiler room to contain smoke detector, fixed 190°F (88°C) heat detector, and remote station intercom outlet.*

Fig. 31.3 *Signal systems in a residence. (a) Electrical signal equipment plan—lower level. (b) Electrical signal equipment plan—upper level. (c) Symbol list for signal equipment. (d) Signal equipment riser diagram.*



(*c*)



(*d*)

Fig. 31.3 *(Continued)*

the following descriptions consider such systems separately, despite the clear trend toward consolidated control.

Residential fire alarm systems are covered in Chapter 25. The components and design of such systems, including detectors, circuit arrangement, and the like, are also discussed there.

Table 31.1 lists the systems and equipment found in the residence shown in Fig. 31.3, organized by the functions of source, processing, and indication. Note that the fire alarm, smoke detection, and intrusion alarm systems have been combined into a single system. This simplifies operation and avoids unnecessary equipment duplication. As the more complex systems are discussed, it will be seen that the basic functions remain unchanged.

As shown in Fig. 31.3, a single control panel can serve multiple residential systems. An annunciator, either integral with the panel or in a separate adjacent enclosure, displays the nature and location of the alarm device that has "tripped." A riser diagram for this residence is shown in Fig. 31.3*d*. The alarm devices themselves are not shown on the riser because they appear on the plans.

TABLE 31.1 Elements of Residential Signal Systems

System Type	Signal Generator	Signal Processor[a]	Signal Transducer
Fire alarm	Temperature and smoke detectors	Control cabinet(s)	Bells, siren, annunciator, buzzer
Intrusion alarm	Door and window switches, motion detectors	Control cabinet	Bells, buzzer, annunciator, siren
Emergency call system	Pull, pushbutton	Control cabinet	Bells, annunciator, corridor lights
Intercom	Microphone, speaker–microphone	Amplifier	Speakers in various stations

[a]Proper wiring and switching are included under this heading in all cases.

31.4 RESIDENTIAL INTRUSION ALARM SYSTEMS

Although any or all of the devices described in Section 31.2 may be used, residences normally utilize door and window magnetic switches, as well as PIR and/or motion detectors, as shown in Fig. 31.3. A switch at the end of a long cord is also often provided so that a resident may set off the alarm manually if an intruder is heard. If the system employs the same audible signal devices as the fire system, the resulting sound should be distinctive so that the nature of the alarm can be discerned aurally. Intrusion alarm systems can be continuously supervised by connection with central stations of security companies that monitor the system and either respond directly to an alarm call or notify local police of any illegal entry.

31.5 RESIDENTIAL INTERCOM SYSTEMS

Interest in home intercom systems seems to come and go. Although available with various features, a basic intercom system comprises one or more masters and several remote stations, one of which monitors the front door, allowing it to be answered from various points within the home. Where desired, a closed-circuit TV system can be added so that visual identification at entrances, in addition to voice communication, is available. In general, master stations allow selective calling, whereas remote stations operating through the masters are nonselective. The systems are particularly useful when left in the open (monitor) position for remote "babysitting." The applicability of such systems to residences with outbuildings should be apparent. As the wiring is low voltage and low power, multiconductor color-coded intercom cable is generally used, run concealed within walls, attics, and basements.

Systems are also available that impose voice signals on the house power wiring. This has the advantage of eliminating separate wiring and making remote stations portable—they are connected simply by plugging into a power outlet.

31.6 RESIDENTIAL TELECOMMUNICATION AND DATA SYSTEMS

Prior to court decisions permitting users to install their own telephone equipment, the actual wiring within a structure was done only by the utility in the user's raceway system. For some years now, work beyond the service entrance may be done by the owner in a fashion similar to other signal work. In residential work, the telephone company normally follows the route of the electric service, entering the building overhead or underground as desired. In both cases, a separate service entrance means must be provided: if aerial, a sleeve through the wall; if underground, a separate entrance conduit. Unless a residence has many entering lines, no source of power is required for the telephone equipment.

Wiring of telephone instruments *after* completion of a residence requires a surface-mounted cable that, even if skillfully installed, is unsightly at best and is usually completely objectionable. Prewiring consists of running the cables within the wall framing and into empty device boxes to which instruments are later connected. The huge increase in the number of private residences with multiple phone lines, dedicated fax lines, and special high-speed data transfer lines connected to home office outlets has made telephone planning as much of a necessity as planning for any other system. This is not only true where residences are designed with a dedicated working-office space. The ease with which modern telecommunications has made it possible to work at home is resulting in an exponential increase in work-at-home situations. Failure to provide for multiple lines with adequate distribution is improper planning. In this regard, a locally franchised telephone company's technical representative can offer valuable planning advice. The system of raceways, boxes, and outlets dedicated to communications systems of all sorts, generally excluding audio signals, has come to be known as *premise wiring*.

31.7 PREMISE WIRING

As noted in Section 31.6, premise wiring refers generally to communication system wiring, including raceways and outlets, and, paradoxically, frequently *not* including wiring. The "wiring" is installed by the various communication contractors and includes fiber-optic (FO) cabling under the category of wiring, despite the fact that wiring is traditionally understood to be metallic. The use of FO cables for most data cabling will undoubtedly increase in the near future because of their proven advantages in bandwidth, freedom from interference, and high-level security.

Most premise wiring raceways are surface-mounted because access is frequently required and

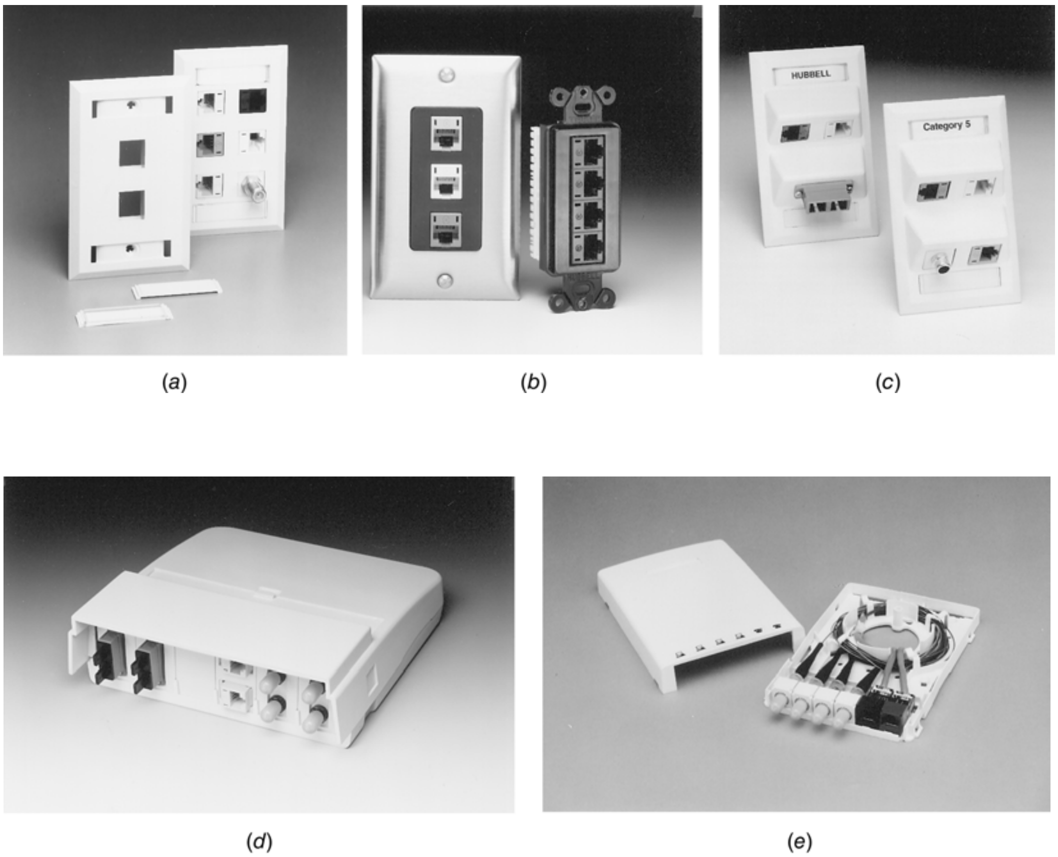


Fig. 31.4 *Typical boxes, devices, and plates used in data and telecommunication wiring systems. (a) Single- and double-gang flush wall plates with various jacks and connectors. (b) Communication outlets styled to match standard rectangular electrical wiring device plates. (c) Angled faceplates with a variety of jacks and connectors. (d) Multimedia outlet that accepts both copper and fiber-optic (FO) cable connections. (e) Multimedia FO outlet with a built-in storage spool for storage of spare FO cable. (Photos a–d courtesy of Hubbell Premise Wiring; photo e courtesy of Panduit Corp.)*

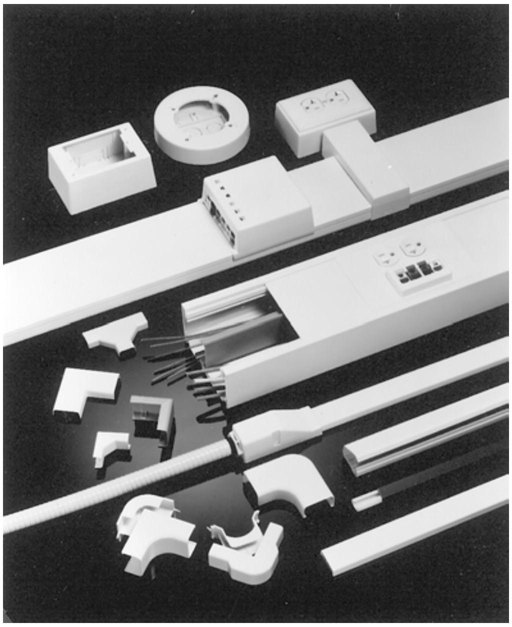


Fig. 31.5 *A range of raceway sizes and shapes is available to meet all signal cabling requirements. (Photo courtesy of Panduit Corp.)*

because data cables are often preterminated, making it difficult to pull them into recessed raceways. Finally, premise wiring raceways are usually large, and as such are much easier and more economical to install as surface-mounted units. Figures 31.4 and 31.5 show a few of the hundreds of devices and raceways used in premise wiring, also referred to as *wire management*. See also Fig. 28.21 for a cutaway view of a typical premise wiring raceway.

MULTIPLE-DWELLING SYSTEMS

See Chapter 25 for a description of multiple-occupancy residential fire detection and alarm systems.

31.8 MULTIPLE-DWELLING ENTRY AND SECURITY SYSTEMS

Apartment houses and other large residential buildings often combine the functions of access control with the familiar lobby-to-apartment communication system. The most basic system is a series of pushbuttons in the lobby and an intercom speaker or telephone with which to communicate with residents. At the other end, the tenant has a speaker microphone plus a lobby door-opener button. This system can also be arranged to utilize the tenants' regular telephones. When the number of occupants is large, an alphabetical roster is added to the apartment-button panel to avoid the nuisance of scanning all the apartment names when the sought party's apartment number is not known. When the number is larger yet, a simple pushbutton per apartment arrangement becomes cumbersome, and is usually replaced by an alphabetical tenant register plus a dial or button phone. Closed-circuit television is frequently added to the lobby system, enabling the occupant not only to converse with, but also see, the caller. Such a system increases the electrical contract cost for an average apartment house by 5% to 7%.

In addition to the security provisions provided by apartment-to-lobby audio and video connections, additional security and alarm devices are often used, such as emergency call buttons within the apartments. These perform alarm functions required to deal with an intruder who manages to bypass the lobby security system. In geriatric housing units, these buttons typically *unlock* the apartment door to allow helpers to enter if summoned by lights and alarms. In luxury apartment buildings, apartment doors can be monitored from a central security desk and any unscheduled door movement be subject to immediate investigation. These systems are custom-designed to meet the needs and requirements of the owner.

A security problem applicable to all facilities, including residential ones, involves limiting entry to unsupervised areas to authorized persons (i.e., access control). The problems with keys and locks are well known, despite advances in that field. More sophisticated means include magnetic cards and electronic combination locks, which, because of the ease of code changes, are particularly useful in residential facilities that cater to transients.

Another aspect of security that is particularly appropriate to housing for the elderly and handicapped, although applicable to all housing installations, is the emergency call system. The purpose of this system is to alert *outsiders* to an emergency situation *inside* a closed apartment. This alarm system is essentially a way to call for help in time of illness or other distress. Many construction and housing codes include descriptions of the required equipment. Most often they prescribe a call initiation button in each bedroom *and* bathroom that will register an audible (alarm) and visible (annunciated) signal at a location that is monitored, locally or remotely, 24 hours a day. Additional signals are required in the floor corridor and at the apartment, the purpose of which is to alert immediate neighbors to a distress call.

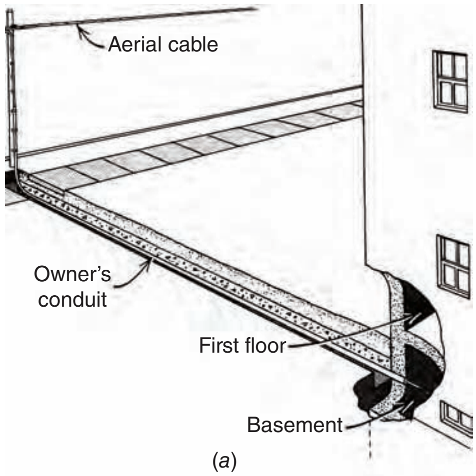
31.9 MULTIPLE-DWELLING TELEVISION SYSTEMS

All modern multiple-dwelling residences supply each room with one or more cable/Internet outlets. The "cable" jack may supply house signals from a rooftop satellite dish or cable TV provider. As these systems are always subcontracted, the design requirements in new construction include a system of empty conduits connecting to cable pulling points in cabinets. Raceways should be sized liberally because of the constant expansion of options in the electronic entertainment field. As pointed out previously, the ideal raceway for signal cabling is 100% accessible (i.e., a surface-mounted raceway with a removable cover). However, this solution is rarely used in new work because of its unsightliness, plus the fact that, for most cabling, concealed raceways are adequate. In low-budget construction, only floor and wall sleeves are supplied, and coaxial cables are run exposed in residential spaces. The cable contractor arranges for the electric power needed for any local amplification. Normally, a 15-A dedicated circuit is sufficient.

31.10 MULTIPLE-DWELLING TELEPHONE SYSTEMS

As in the small residence, telephone service normally follows the same entrance path and method of entrance as the electric power service. For the sake of economy in underground construction, the two services often share the same trench, although in different raceways, and utilize twin manholes where these are required. Typical entrance arrangements for any large building, residential or other, are shown in Fig. 31.6.

The service entrance space requirements vary with the size of the building and the telephone capacity. For a small apartment house of the garden or three-story type, a clear wall space of 4 to 6 ft (1.2 to 1.8 m) is sufficient. A terminal (equipment) room is required only in large buildings (see Section 31.21). The telephone system is one part of the overall telecommunications system in most modern residences, preparations for which fall into the premise wiring area discussed previously.



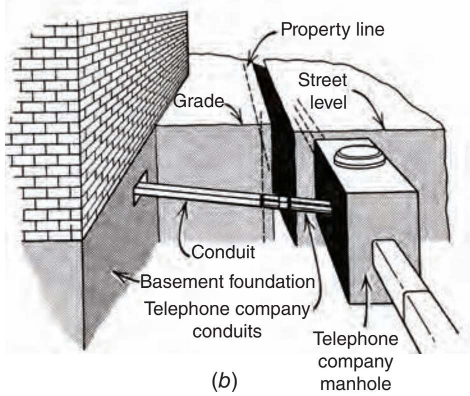


Fig. 31.6 *Telephone cable may enter a building underground after originating on overhead lines (a) or via manholes (b).*

Therefore, generalizations are not useful, and planning must consider the type of occupancy and future requirements.

Rental apartment buildings and dormitories differ from commercial structures in that the layouts of all floors are similar, so that the arrangement of risers is relatively simple. It is common practice to utilize cable only in risers that extend through vertically aligned closets in apartments. To accommodate these cables, sleeves through the floor between closets are necessary. If a riser is located in a shaft other than a closet, conduit is normally utilized to allow for easy installation, protection, and repair. If the location is accessible, as in an alcove, only a sleeve is provided. When the riser is located outside the apartment, each dwelling unit is connected to the riser by a conduit with a junction box at either end. Beyond the apartment service point, the individual rooms can normally be prewired entirely without conduit or with only a few short sleeves. In condominium and coop structures, large raceways are run from the service entrance point to cabinets on each floor of the building. From terminal devices in these cabinets, the required service can be extended into each apartment. Prewiring of the apartment avoids the unsightliness of exposed cabling or of cabling within surface raceways.

31.11 HOTELS AND MOTELS

(a) Security

Because of the transient population of these facilities and the need to provide maximum service and security to guests during their stay, the principal problem in addition to room access security is hotel equipment security (i.e., prevention of what is euphemistically known as *shrinkage*).

Room access security. The ineffectiveness of key locks in preventing undesired entry (even in private homes) is well known; in hotels, a key is little more than a psychological barrier. As a result, most modern hotels have installed electronic room locks whose opening device code is changed with every new guest. These locks may: (1) have changeable coding accomplished only from a central lock–security console, (2) be a magnetically or electronically coded-card type (Fig. 31.7), or (3) be a programmable electronic lock and coded-key type of device (Fig. 31.8). All of these systems have advantages and disadvantages, depending upon the number of rooms, whether the installation is new construction or retrofit, and the average length of the guest stay.

Fig. 31.7 *Electronically coded card keys are often used in hotels. The coding is changed after each room use. (Courtesy of Bruce Haglund.)*

Equipment security. Expectations for amenities require that guest rooms be equipped with a television and possibly a DVD player, though now movies are typically handled as on-demand through cable companies; meeting rooms with TV, DVD and/or VCR, projectors, and computer terminals; and that these and other devices be made available for guest use either as part of the room fee or on a rental basis. Theft control is a specialty on its own and is beyond the scope of this book. One such system (equally applicable to equipment in hotels, schools, office buildings, and industrial facilities) senses the disconnection of equipment from its power connection (wall plug) and transmits an alarm over the power lines to an annunciator at a selected control location. This arrangement has the advantage of alarming immediately on equipment removal, thus normally permitting appropriate retrieval action to be taken in time.

Fig. 31.8 *This electronic door-locking system uses a programmable electronic lock (a) with a non-duplicatable fixed-code metal key (b). The lock, which can be reprogrammed by the use of a portable programmer, reads the key code with an internal infrared reader. The keys, which can be programmed with up to 1.5 million codes, are discarded after use. Each lock accepts up to 3000 different codes and can be programmed in two modes: passage mode (to admit a user during a specific time slot) and time mode (to accept specific keys during specific time slots). In addition, the locks can be audited to reveal access records, invalid attempts, activation/deactivation, and mechanical key override.*

(b) Telecommunication, Data

The telephone and data communication system in large modern hotels is important and complex. Hotels catering to businesspersons must provide access to the Internet that can be used at the very least in rooms dedicated to that purpose and, almost universally today, in guest rooms as well. Therefore, the building designer must provide adequate raceway (and cabling) facilities, as discussed in Section 28.17. The current practice of holding business meetings and technical conferences in hotels also requires that conference and meeting rooms be arranged for very heavy concentrations of electronic equipment that can be installed and rearranged in short order. This may call for some sort of access floor and modular cabling, as described in Sections 28.25 to 28.30. Meeting attendees are increasingly expecting and demanding wireless Internet access throughout a hotel.

SCHOOL SYSTEMS

31.12 GENERAL INFORMATION

The proper operation of a modern school requires that flexible and efficient signal and communications equipment be available to the administrative and teaching staff. Such equipment, engineered to meet the needs of the individual institution, can improve utilization of staff and student time. School fire detection and alarm systems are discussed in Chapter 25.

31.13 SCHOOL SECURITY SYSTEMS

Although intrusion alarms and security systems are not historical school requirements, this situation has unfortunately changed. Sensing devices on doors and windows can be arranged both to trip local alarm devices and, via auxiliary circuits, to notify police headquarters. Often, vandals can be frightened off by having the alarm system actuate a protective lighting system that illuminates the building exterior and any desired interior areas, such as record rooms. A perimeter alarm detection system of the types described in Section 31.2 can be installed in particularly vandalism-prone areas to assist in preventing entry to school premises after hours. Although expensive, they are very frequently cost-effective.

An exit-control alarm is a type of exterior door security device applicable to schools (and other facilities) with doors that are locked from the outside but that must be openable from the inside in the event of an emergency. This device (Fig. 31.9) alarms as desired (i.e., audibly or visually, locally or remotely) when a monitored door is opened. It is normally equipped with a timed bypass that allows

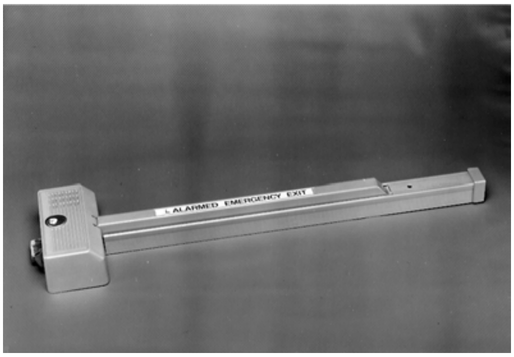


Fig. 31.9 *Delayed-egress exit alarm. When the bar is pushed, an alarm sounds immediately, but egress is delayed 15 seconds to permit security personnel to investigate before the door release operates. In the event of fire or another emergency, the door releases instantly. The alarm can be bypassed and reset by key only. (Courtesy of NAPCO.)*

authorized personnel to key-operate the bypass but prevents the door from being held open without alarming. One model of door-opener alarm requires a continuous pressure on the door-opening bar for 10 to 20 seconds before the door opens, with the alarm being activated immediately on application of pressure. This arrangement (usable only where fire codes permit) allows sufficient time for the facility's staff to investigate an attempted exit before the door opens, and is applicable only where exit control is the overriding consideration. As mentioned in Chapter 25, stair and exit-door exit locks can be arranged to be centrally released from a fire control center.

31.14 SCHOOL CLOCK AND PROGRAM SYSTEMS

The clock system and the program system were once separate and distinct, sharing only the timekeeping facilities provided by a master clock. Now that electromechanical programming devices are effectively obsolete, the two systems are actually one, but the traditional two-system name remains. As shown in Fig. 31.10, the heart of the system is the time base (electronic clock). This is the same device that provides timing for all programmable switches and controllers. In a clock and program device, it controls clock signals, audible devices, and, if desired, other switching functions.

The clock system may use analog clocks (with hands), digital units, or both. The former are usually locally powered, and a correction signal is periodically transmitted via dedicated wiring from the master clock at the controller. This same controller continuously transmits a binary-coded signal to digital "satellite" clocks, which can be either of the self-illuminated light-emitting diode (LED) type or of the liquid crystal display (LCD) type. LCD units are easily visible only in high ambient illumination and when viewed directly (not at an acute angle). LED units are best applied in areas of low ambient illuminance. Large-face analog clocks are easily visible in all ambient light situations.

The programming function of the controller serves to delineate audibly the various time periods

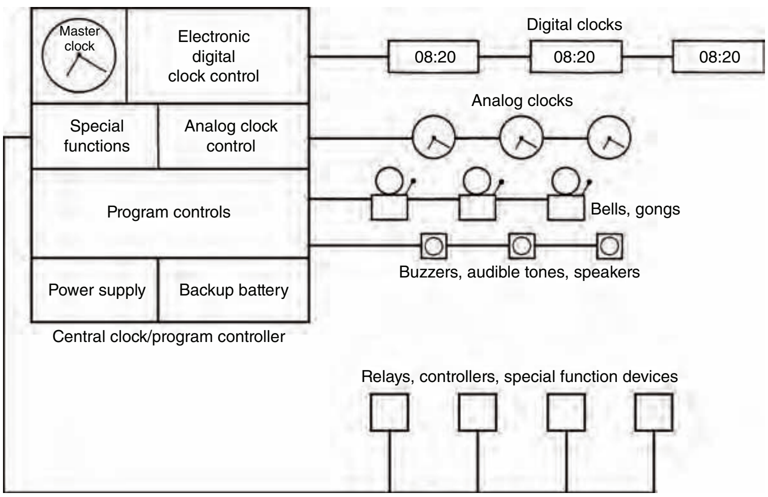


Fig. 31.10 *A central clock and program device uses its electronic time base to control clocks of all types, time-based audible signals, and event controllers.*

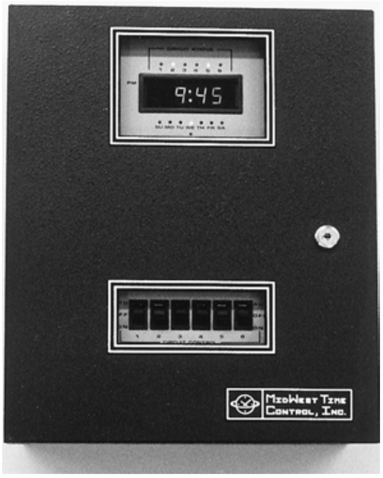


Fig. 31.11 *Typical microprocessor-based master time clock and program device. This unit, which measures 14 × 12 × 5 in. deep (355 × 305 × 127 mm), provides time correction signals to synchronous wired clocks of the digital or analog type, and can be adapted to control minute impulse clocks. Programming of output circuits can be daily or weekly, and can accommodate daylight saving, holiday, and leap-year updates with a total program capacity in excess of 600 events. Programming is done locally or via a remote computer. This type of device is applicable to any facility requiring a clock and/or program system. (Courtesy of Midwest Time Control Inc.)*

into which the school day and week are divided. A single-circuit unit is utilized in an institution that operates entirely on one schedule, such as an elementary school on a morning period–lunch–afternoon period regimen. For a school employing different schedules for its various parts, the controller can provide multiple program schedules on different circuits, depending upon its design. Controllers are user-programmable and are normally provided with a crystal-controlled master clock to ensure accurate timekeeping, regardless of line frequency variation; a backup power source to maintain user programming and master-clock local display; and various conveniences such as daylight saving time correction, security arrangements, event timers, and so on. If desired, the clock and program controllers can also be used for mechanical system control by the simple expedient of adding relays and switching devices, as shown in Fig. 31.10. Typical clock and program controllers are shown in Figs. 31.11 and 31.12.

The audible devices in a program system may be bells, gongs, buzzers, horns, or a tone reproduced on a classroom loudspeaker. The last system has the following advantages:

1. Clear audibility in each classroom, with an adjustable volume to accommodate both quiet and noisy areas.
2. No possibility of confusion between the program tone and other signals such as fire alarm gongs.
3. Multiple use of the speaker unit for classroom sounds as well as program tones.
4. Complete flexibility of programming that is not possible with hall gongs. This is particularly desirable in schools with special programs for particular groups of students.

31.15 SCHOOL INTERCOM SYSTEMS

Various types of intercom systems are available, depending on the needs of the school building involved. In small schools, a simple wired intercom system connecting the various offices is usually sufficient. This is supplemented by outside telephones in the administrative offices and a functional paging system that is normally part of the school's sound system. With larger buildings and correspondingly larger numbers of extensions and multiple-function demands, more sophisticated equipment is required. The unit illustrated in Fig. 31.13 is typical of modern school intercom equipment and is actually a private telephone system with considerable flexibility. Such a system is generally interfaced with the school sound system and may provide these functions:

1. Intercom between staff members and offices
2. Direct communication with classrooms, including selective and all-call capability

Fig. 31.12 *User-programmable master clock and program controller. This unit has nonvolatile memory, eight program zones, automatic daylight saving time and holiday adjustment, and a maximum of four schedules; it is usable with most types of secondary clocks. (Courtesy of Rauland-Borg.)*

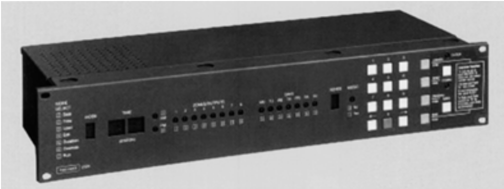


Fig. 31.13 *Intercom controller. The illustrated microcomputer design interfaces with the existing telephone system. In addition, it provides paging, tone distribution, and program distribution, with control from a telephone. The unit, which measures 19 in. × 9.5 in. × 3.4 in. high (483 × 241 × 86 mm) and weighs 9 lb (4 kg), also has a built-in master clock. (Courtesy of Rauland-Borg.)*

3. Paging zone, group call, and conference call functions
4. Interconnection with the outside phone system
5. Class-change signals via interface with the master clock system
6. School intercomputer communication via a network

A combination program/intercom controller is shown in Fig. 31.14. These systems use direct push-button dialing and programming, thus eliminating the need for switchboards and operators. All stations are coded with three-digit codes, and all switching is solid-state, minimizing maintenance problems. Such systems are adequate for all but the largest institutions.

31.16 SCHOOL SOUND SYSTEMS

An integrated sound-paging-radio system designed for school use offers several modes of operation and considerable flexibility. Its function is to provide a means for distributing signals from recordings (CDs, DVDs, tapes), broadcasts (AM/FM), or live sound to preselected areas of the school. Thus, a simple system might provide a CD player and single microphone input and a single channel to all the speakers in the school, whereas a complex system can be arranged to operate with three simultaneous input signals distributed to six different areas of the school (see Fig. 31.14).

Fig. 31.14 *Compact program/intercom control center. This unit, which measures 20.5 × 11 × 8.5 in. high (521 × 280 × 216 mm), has a separate power amplifier for intercom and program material. It distributes program material or provides intercom with 25 loudspeaker locations and has additional capabilities, such as emergency/all-call paging, tone calling, time signal, night bell, and telephone paging. Program material is accepted from separate external sources. (Courtesy of Bogen Communications Inc.)*

A conventional system consists of a control console containing most of the input units, amplifiers, switching devices, and connections to the remote loudspeakers. The input units may comprise one or more AM/FM tuners, a VCR, CD/DVD player, tape deck, and microphones. One microphone is normally located at the console, with others in the principal's office, auditorium, school office, or other selected locations. If desired, microphone outlets can be spotted around the school, and a spare microphone and stand supplied that can be plugged in at any of these points (Fig. 31.15).

Loudspeakers, located in classrooms, gymnasium, auditorium, cafeteria, and outdoors, receive the amplified signal through the switching mechanisms located in the console. The function of these switches is to deliver the program material to the various loudspeaker circuits, called *program lines*. Thus, using a system with multiple amplifiers, music can be piped to the cafeteria, an educational broadcast program to selected classrooms, and instructions to an outdoor gym class or team during practice. An all-call feature also allows announcements to reach all speakers in the system simultaneously. The intercom system discussed previously can be interconnected with the sound system to allow conversation between classrooms and the console or other points. A small system can be contained in a compact desktop console (see Fig. 31.14). A large system frequently requires a separate console. A console is usually built in a desk arrangement, and it is advisable to provide sufficient space for it and for the person who operates it. Often an alcove of 30 to 50 ft^2 (2.8 to 4.7 m^2) is reserved for it and a library of recordings.

Loudspeakers may be placed flush or in surface baffles at the discretion of the designer. Gymnasium, cafeteria, and auditorium units are normally flush-mounted in the ceiling. For such large areas, it is well to provide a volume control, enclosed in a recessed wall box with a locking cover. A common

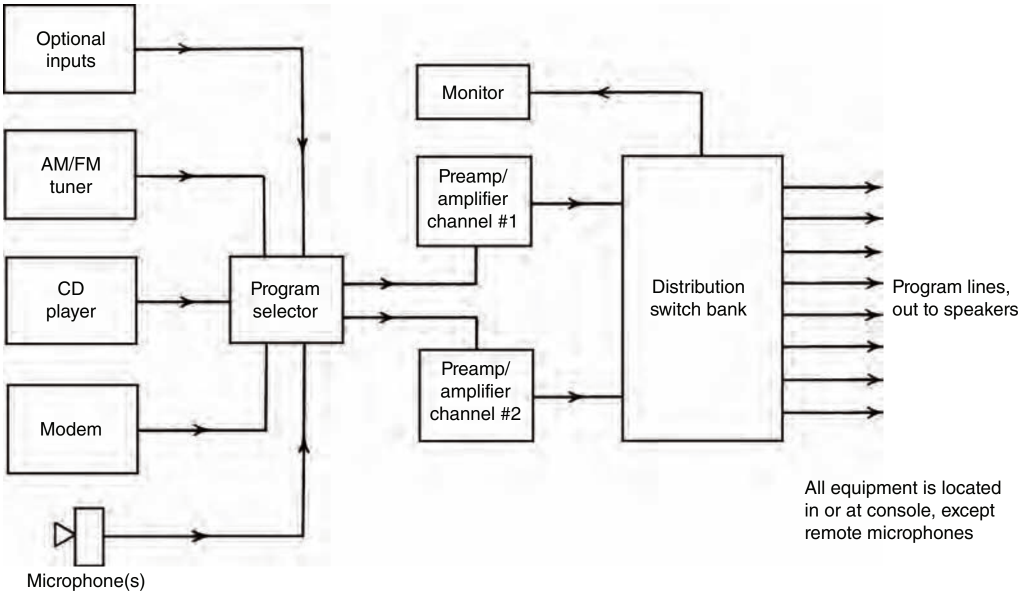


Fig. 31.15 *Block diagram of a two-channel sound system. Options that can be added to the console are a tape deck, private telephone communications, modem connection, and equipment for rebroadcast of signals between areas. An intercom and a master clock and program can also be incorporated or interconnected.*

variation of this system uses separate subsystems for the cafeteria, auditorium, ball field, and other areas that utilize sound equipment frequently. These smaller systems have their own input, amplification, and control devices but utilize speakers in common with the central console. Normally, the console has an override feature that allows it to override local systems.

For a discussion of high-quality sound systems required for recital halls in music schools and the like, refer to Sections 23.16 to 23.18.

31.17 SCHOOL ELECTRONIC TEACHING EQUIPMENT

This area of technology, like so many others that utilize computers, is growing and changing so rapidly that almost anything written about it is immediately out of date. This section simply outlines present and projected near-future uses of electronic teaching equipment. Figure 31.16 shows in block diagram form the arrangements possible with current technology.

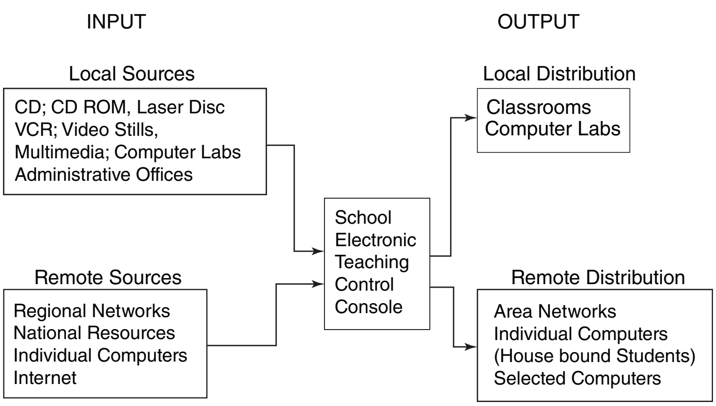


Fig. 31.16 *Block diagram of connections to an electronic teaching console. Inputs change as technology changes.*

(a) Passive-Mode Usage

This category encompasses all recorded material, in whatever form, that is available to the student via some form of information retrieval technique. This includes printed, audio, and video material in conventional and electronic library forms.

(b) Interactive Mode

Here students use a computer teaching terminal interactively to study at their own pace on a one-to-one basis, with the computer acting as a tutor. Modern teaching programs sense the students' weak points (as do good teachers) and emphasize them in teaching. The building designer must be aware of the rapid developments in this field at all educational levels, including elementary school, in order to make adequate electric power, cable raceway, lighting, and HVAC provisions.

OFFICE BUILDING SYSTEMS

31.18 GENERAL INFORMATION

This section addresses systems found in all office, professional, and sales-type buildings. Such buildings house tenants with varying schedules and requirements. This diversity must be considered in the design of the signal and communications systems for such buildings.

Although in many medium-sized and large buildings the various control, alarm, and security functions are combined in multiuse apparatus and consoles (discussed later in the chapter), the basic systems are essentially separate despite having shared-use equipment. They are discussed individually to demonstrate function and equipment, and then as combined to show economies and modern practice.

31.19 OFFICE BUILDING SECURITY SYSTEMS

Although automatic surveillance systems *are* applicable to office and mercantile occupancies, they are more frequently found in industrial facilities and are discussed under that heading. Office buildings normally utilize some type of manual watchman's tour system so that surveillance of unoccupied areas is conducted on a regular basis.

The simplest type is nonelectric and comprises a number of small cabinets, each containing a key, placed at intervals around the interior and exterior of the building. The watchman uses these keys to operate a special clock that he carries about, thus recording the exact time at which he "clocked in" at any specific location. Alternatively, the clock is wall-mounted and the guard carries only a key (Fig. 31.17). A computerized version of this system is available that simplifies station check-in, automatically records guard visit data, and provides a hard-copy printout.

Guard tour systems are also available that permit constant supervision and are particularly effective where more than one person is on duty. Such systems show on a panel the location and progress of the watchman by means of lights that glow when the device at each location is operated. Because part of the effectiveness of these systems lies in the timing of the tour, a system can be arranged to sound an alarm if a particular station is not operated within a specific time period. Telephone jacks spaced at points along the guard's route allow the guard

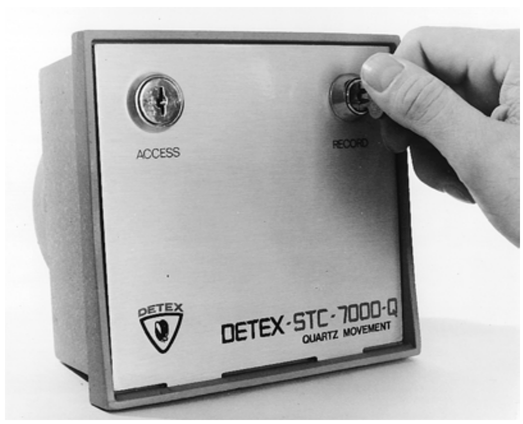


Fig. 31.17 *Watchman's tour station. Here the clock and recording tape are inside. The station is operated by simply inserting a key, as shown, and giving it a quarter-turn. An alternative version of this system, commonly used, consists of a portable clock and tape operated by a key in a wall box at each station. (Courtesy of Detex Corp.)*

to communicate with the supervising office or other point without interrupting the scheduled tour. For protection of areas housing extremely valuable items or documents, an intrusion alarm system may be employed.

31.20 OFFICE BUILDING COMMUNICATIONS SYSTEMS

Planning for this type of system requires considering four functions, which are frequently melded into a single network:

1. Intraoffice voice communication, or intercom
2. Interoffice and intraoffice data communication using telephone and communication cabling
3. Outside-the-building communication via telephone company (or data) lines
4. Paging function

Today, in most locations, the user has the choice of purchasing or leasing as much of the communication system as is desired. In other words, the communication system, including cables, instruments, switching equipment, and so on, can be all privately owned, all supplied by the local telephone company, or acquired in almost any other arrangement desired. Except for a small interoffice intercom, however, duplication is eliminated—that is, the same instruments and switching equipment are used for both intercom and outside connection.

What to buy, rent, or lease constitutes an economic decision because the required functions are satisfied by either private or telephone company equipment.

31.21 OFFICE BUILDING COMMUNICATIONS PLANNING

Planning for the telephone and other communications equipment in an office building is of prime importance because of the large amounts and critical locations of required space. Therefore, it must be done simultaneously with other space planning. Exact requirements for office space are generally unknown at the time of design, and even if they were known, planning would have to account for changes in space usage as well as increased communications and data transmission services. For this reason, all planning is based on usable office area. Planning is essentially focused upon spaces, from incoming service space to final instrument locations, because cabling and equipment are furnished and installed either by a private telephone equipment supplier or by the telephone company.

The planning information that follows is applicable to office buildings with average telephone and data transmission loads. Buildings whose tenants include brokerage houses, insurance companies, headquarters of multibranch operations, and other heavy telephone and data transmission users may need more space. Advances in technology, however, including the use of FO cables, act to reduce equipment size and space requirements. As a result, the best course of action is to design for current requirements with a reasonable estimate for future needs and technologies based upon advice from experts in the field.

Space is required for:

1. A service entrance room that houses incoming cable (network cable), terminated empty conduits for expansion and data cables, a network cable splice box, connection (network interface) cabinets, and equipment required to interface the building's equipment, including telephones, modems, fax machines, and the like, to the main connection cabinets. This space is usually referred to as the *equipment room*.
2. Riser spaces (shafts) and riser closets. These are stacked vertically and carry main cables.
3. Satellite closets where required.
4. Horizontal distribution between closets and devices, including conduit, boxes and cabinets, underfloor raceways, and over-the-ceiling systems.

A riser diagram of a typical system is shown in Fig. 31.18.

(a) Service Entrance

At least two 4- or 5-in. (100- or 125-mm) conduits extend from the exterior service connection to the basement or ground-floor service equipment room. One conduit will contain the service (network) cable; the other(s) is a spare. Spare conduits should be terminated 12 in. (300 mm) above the finished

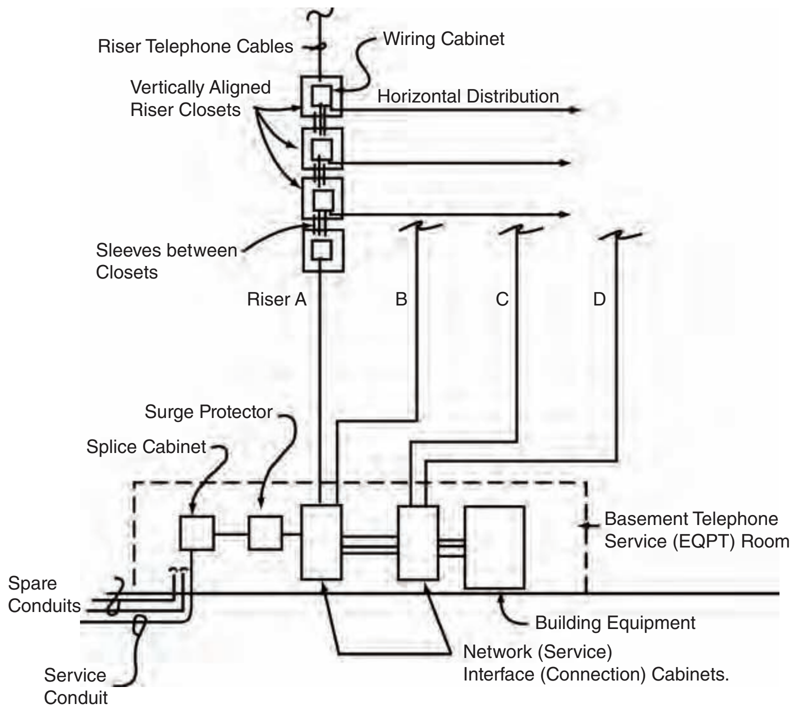


Fig. 31.18 *Riser diagram of the telecommunications system raceway and space arrangements for a typical commercial office building.*

floor (AFF) of the equipment room, in a threaded fitting, and sealed against entrance of dirt, moisture, or rodents. The service entrance cable terminates in a splice box or cabinet, from which, in large buildings, additional cables extend to one or more wall cabinets, each measuring about 3 ft wide, 6 ft high, and 2 ft deep (0.9 × 1.8 × 0.6 m). Each cabinet can serve a maximum of 30,000 to 100,000 ft^2 (2790 to 9290 m^2) of tenant area, depending upon the density of service required. To accommodate these cabinets from which risers extend, a clear wall space of 6 ft (1.8 m) for every cabinet should be provided. This wall area should be covered with ¾-in. (20-mm) marine plywood for cabinet mounting. A 1-in. (25-mm) PVC conduit should extend between cabinets from a suitable electrical system ground point, with a ground wire sized according to telephone company requirements. The room should be dry, ventilated, well lighted for close work in wiring and color recognition, and supplied with at least two 20-A duplex convenience outlets on a separate circuit.

In the event that additional connection, switching, or communication equipment is required, the project electrical engineer should obtain the equipment size and electrical requirements, provide the necessary space requirements to the architect, and design the electrical elements. In large equipment rooms, circulation and egress must be considered, as well as emergency light and power.

(b) Riser Shafts

These accept the cables extending beyond the equipment room and carry them vertically through the building. Connection from the wall cabinets in the equipment room up to the riser shaft should preferably be in conduit.

The riser shafts provide means for the cables to extend vertically and terminate at each floor. Ideally, the riser spaces comprise a series of vertically aligned closets connected by ½- or 4-in. (12- or 100-mm) sleeves set in the floors and extending 1 in. (25 mm) above the floor. Sleeves are preferable to slots because they can easily be sealed and fireproofed; slots cannot. A minimum of four 4-in. (100-mm) conduit sleeves should be installed between closets vertically, plus an additional 4-in. (100-mm) sleeve for every additional 50,000 ft^2 (4645 m^2) of office space to be served. It is preferable to separate communications closets from electrical power closets. Where multiple risers are used, shafts should be interconnected by several 2-in. (50-mm) conduits to allow for interconnection of systems. Riser cables are also known as *backbone* cables.

(c) Riser Closets

Here, cables from the riser system are interconnected to switching and power equipment, as well as to the cables that radiate from the closet to station locations throughout the floor area. These closets may also be called *zone closets* or *apparatus closets*, particularly if they function with an underfloor raceway system. The walls of the closet should be lined with plywood at least ¾ in. (20 mm) thick to support the weight of switching and connection panels, power equipment, terminals, connecting blocks, and other hardware. Each riser (apparatus) closet must be provided with a switched ceiling light and a separate 20-A, 120-V circuit with two duplex receptacles. A source of emergency power is desirable to avoid curtailment of telephone service during power outages.

Riser closets should preferably have a minimum net area of 20 ft^2 (2 m^2) and a minimum clear wall of 5 ft (1.5 m) for cabinet mounting. Each closet can supply telecommunication service for 8000 to 10,000 ft^2 (740 to 930 m^2) of floor area. Telephone equipment being utilized should not be more than 250 ft (75 m) from a closet.

(d) Satellite Closets

Unlike riser (apparatus) closets, satellite closets do not contain switching and power equipment. Their primary use is to provide cable-connecting and -terminating facilities in large, complex buildings, where riser closet space is insufficient.

(e) Auxiliary Equipment Rooms

Where extensive cross-connection is required or tenants utilize private switchboard (PBX) equipment, the required equipment is placed in a relatively small auxiliary equipment room. These spaces, which are actually small closets or alcoves, should contain a 20- to 30-A, 2P, 120/208-V circuit, a 20-A, 120-V outlet, a grounding point, good lighting, and sufficient equipment space. Space requirements vary with each installation and can be obtained from the equipment supplier. Ventilation is essential, as is absorptive acoustic material on the ceiling and at least one wall. Connections between these spaces and other communication equipment closets should be via floor or ceiling ducts or multiple ½-in. (12-mm) conduits.

(f) Horizontal Distribution

Cabling from riser, satellite, apparatus, and equipment closets to individual outlets and instruments can be run underfloor, in ceilings and plenum spaces, under-carpet, or in surface raceways. Because of the large raceway volumes required, conduit is infrequently used. When underfloor raceways are used, a header capacity of 2 $in.^2$ (1290 mm^2) per workstation is reasonable, based on one multiline telephone and one video display unit per station.

(g) FO Cables

Fiber-optic (FO) cables are used in lieu of copper cabling in installations with very heavy data transmission loads, in those using video systems, and/or in applications for which the high-security, low-noise, and broad-bandwidth characteristics of FO are necessary or desirable. Information on space requirements and connection accessories can be obtained from manufacturers. Because cables are often supplied with factory-applied terminations, raceways must be of the large-capacity, full-access type.

31.22 OFFICE BUILDING CONTROL AND AUTOMATION SYSTEMS

As mechanical and electrical systems in modern office buildings increased in complexity, the need arose for a central point of supervision, control, and data collection. This provides a single locale from which to survey and control an entire building's functioning, plus increased opportunities for automation. From a supervisory location, water, air-conditioning, heating, ventilating, electrical, and other systems can be controlled with accuracy and convenience. Data on temperatures, pressures, flow, current, voltage, and the many other parameters of mechanical and electrical systems can be made available instantly so that operational decisions can be made and automated. All systems can be monitored centrally and all alarms instantly and automatically acted upon.

Such *supervisory control centers* are now installed as a matter of course in office buildings. They are equipped with computers that process the data received to make operational decisions intended to optimize system performance. As a result, they can provide a considerable savings in operating and maintenance costs. These systems in their most generalized form are referred to as *building automation systems* (BAS) and are discussed at length in Sections 31.26 to 31.31.

Architecturally, the spaces housing BAS centers require good lighting, good ventilation, and extensive raceway space but little area. Because systems are custom-tailored to a specific building, no guidelines can be stated for space requirements.

INDUSTRIAL BUILDING SYSTEMS

31.23 GENERAL INFORMATION

All industrial facilities, ranging from a loft housing a small hand-assembly plant to an immense steel manufacturing plant, require a variety of signal and communication equipment. Fire alarm systems for industrial buildings are discussed in Chapter 25. Audible alarms for building security in any industrial facility must be selected with the likelihood of high ambient noise levels in mind. See Figs. 31.19 and 31.20 for recommendations.

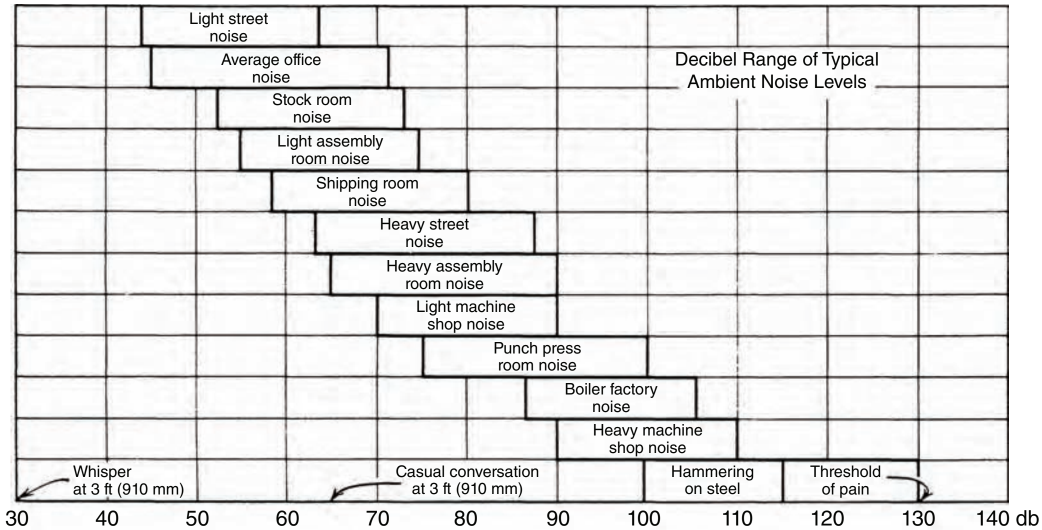
31.24 INDUSTRIAL BUILDING PERSONNEL ACCESS CONTROL

The design and engineering of personnel access control systems is a specialty that has burgeoned since the late 1980 s and is now an independent profession. The increasingly diverse variety of identification technologies, plus the control and supervisory capabilities of computers, has greatly enhanced the access control capabilities of even a relatively small system. As a result, this section does not attempt to discuss system design, but focuses instead upon the operation and application of the subsystems that compose the whole.

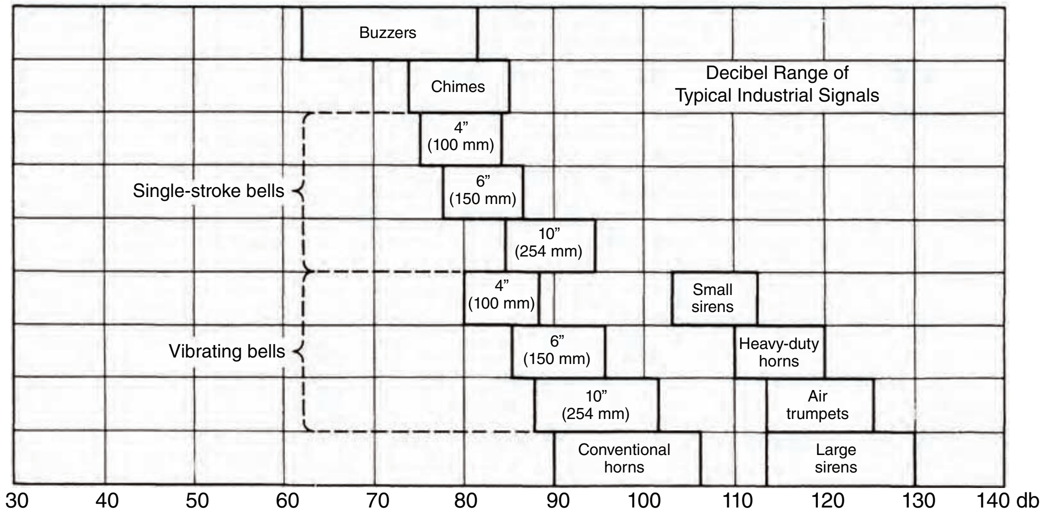
The traditional access control question was always "Who is permitted to pass through a specific portal?" The means by which identification is made to answer this question varies with the importance of access control at that portal. Thus, entrance to a large, multipurpose space used by many people must be rapid and must avoid the delay engendered by a physical barrier. One means commonly used is one or more guards who visually, and in relatively cursory fashion, inspect a badge with an ID photo. The next level of supervised, barrier-free access control may be a "turnstile" that requires presentation of an access card to an electronic proximity reader. One such unit is illustrated in Fig. 31.21. This type of barrier is limited to a maximum pass-through rate of about one person per second. Because these two control methods are generally barrier-free, the action taken on alarm is to activate physical barriers and sound the appropriate alarms.

When a physical access barrier is involved, passage is slow, depending only partly on the identification process. Even with the most rapid electronic identification, a door or other portal closure must be physically released and operated, which can be very time-consuming.

Unattended physical barriers can be released by a multitude of differing identification technologies, depending upon the required level of scrutiny. At the lower end of the security scale are barriers that require some embedded knowledge and/or inspect an object presented by the user, such as a magnetic, bar-coded, or proximity-reader card. Because locks can be controlled electronically and remotely, they can be programmed to give access at certain times only or to specific groups of cards or individual cards only, or to deny access to specific cards (e.g., cards reported lost), or for any other selection criterion. Time-controlled access is flexible; it integrates



(*a*)



(*b*)

Fig. 31.19 *(a) Decibel range of typical industrial noise situations. (b) The decibel rating of typical industrial signals may be compared with the anticipated ambient noise level (a) to facilitate selection.*

extremely well with intrusion security systems because portals can be easily coordinated with changing work schedules, both general and specific. Thus, a person can be barred from an area to which he/she should not have access at some particular time of day (Fig. 31.22).

The most sophisticated identification methods in use today are biometric: examining a specific physical characteristic that is unique to each person. This is considered a higher level of entry control because it identifies a person, not an object. Several of these methods are illustrated in Figs. 31.23 through 31.25.

In view of the plethora of available access-control technologies, access is being redefined beyond its original physical-admittance meaning. Access control today is also used to limit access to copy machines, fax machines, phone lines, and other office facilities frequently used by employees for other than purely business purposes.

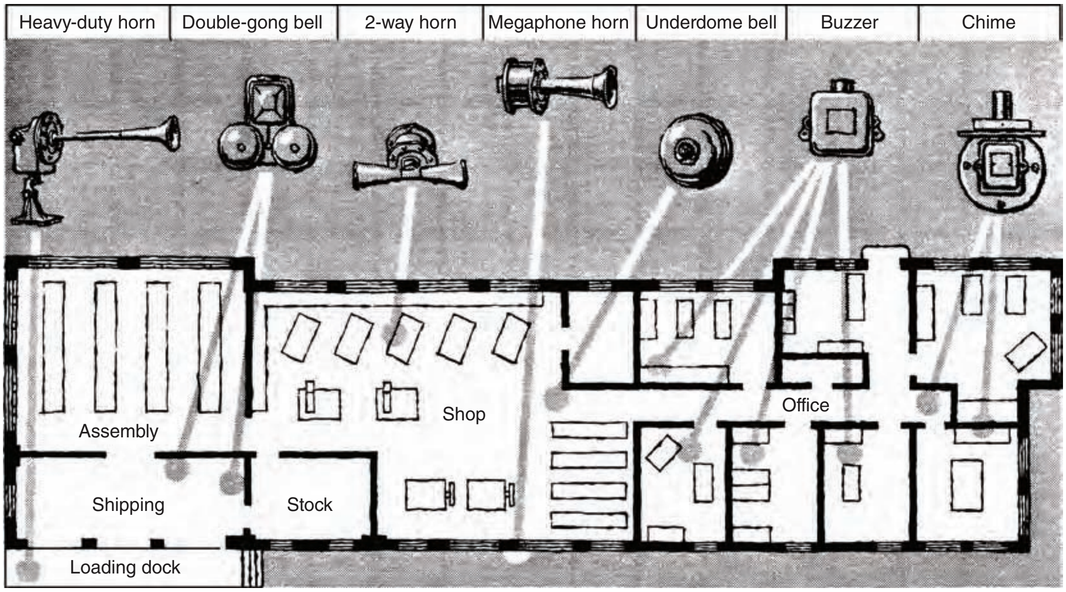


Fig. 31.20 *Plan of a small industrial facility showing suggested locations of typical signals.*

31.25 INDUSTRIAL BUILDING SOUND AND PAGING SYSTEMS

Belt beepers, pagers, and cellular phones are frequently ineffective in industrial facilities because of high ambient noise levels. In such areas, voice paging at high audio levels (see Figs. 31.19 and 31.20), radio-frequency paging calls on earphones or speakers built into sound-reducing ear protection (see Fig. 24.53), and paging calls using paging lights are used. Similar methods are employed in noisy areas for announcements and special voice messages. In less noisy areas, such as offices adjoining manufacturing spaces, sound-reinforced conventional office-type systems are usually employed.

AUTOMATION

31.26 GENERAL INFORMATION

It is important that the distinction between remote control and automation be clearly understood. *Remote control* is simply a technique by which an action that can be performed manually at the device being controlled is performed from a remote location by some intermediate means. The means may be low-voltage wiring (Section 27.32), a high-frequency wired signal (Section 27.34), a wireless signal such as from a household TV/CD/VCR remote control, a similar IR lighting control unit (Fig. 16.24), or a radio-frequency wireless control (Fig. 17.6). In each case there is a single-stage action that is manually initiated. When the signal initiation is nonmanual—that is, *automatic*, from a timing device (Section 27.16), a sensor such as a daylight or occupancy sensor (Section 16.17), or a programmable device such as a microprocessor or computer—the control comes from an *automated* system. The system can be elementary, as just described, in which an automated signal controls a single action. It can also be very complex, with many levels, yet treat only a single function, such as an automated lighting system with sensors activating or overriding scene-presets that activate dimmers and switches. Such a system is referred to as a *stand-alone* (automated) system. When several of these stand-alone systems are interconnected and supervised by a higher-level controller, each is referred to as a *subsystem*, and the overall system is referred to as an *integrated control system*. Such an integrated system, when applied to the individual systems in a building, is referred to as a *building automation system* (BAS).

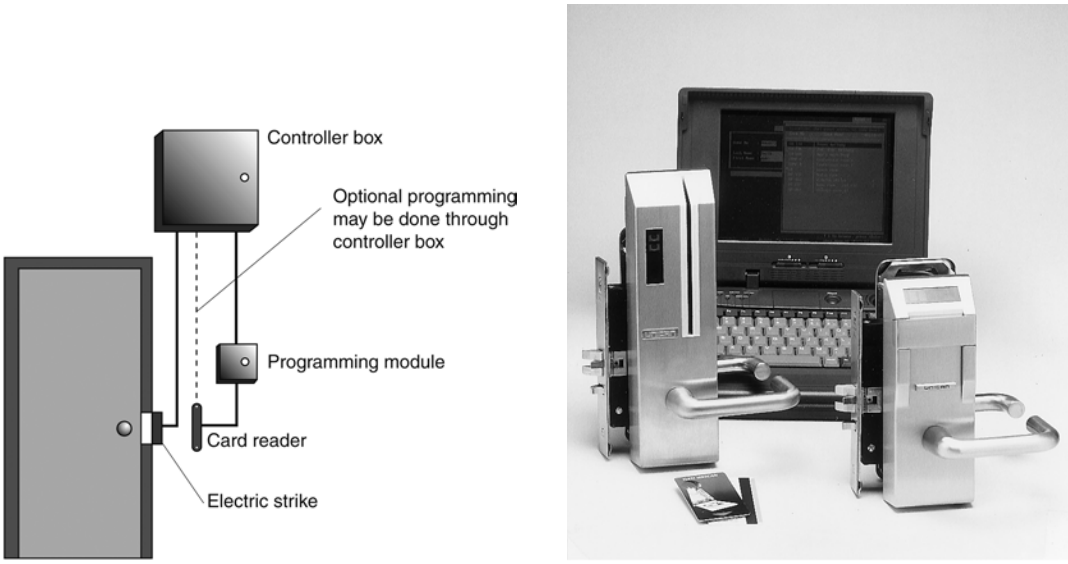
Fig. 31.21 *Optical turnstiles in an office lobby. Turnstiles with barriers, also called "speedgates," are preferred due to the deterrent effect and the obstruction which slows or blocks (with a locking barrier) passage. Such turnstiles require the presentation of access credentials, often a proximity card, but possibly a biometric or smartphone, in order to be granted passage through the lane into the building. Unauthorized access initiates local audible and visual alarms and other measures as designed to secure the building from intruders. Frequently, such optical turnstiles are installed with a guard desk nearby (Photo courtesy of Smarter Security, Inc.)*

31.27 STAND-ALONE LIGHTING CONTROL SYSTEMS

A straightforward stand-alone lighting control system is shown in Fig. 31.26. The initial programming is entered from a laptop computer into the control panel using system (manufacturer's) software. The control panel contains the required microprocessors, timers, and output control devices to establish lighting levels and settings in the entire structure via dimming and switching panels. In addition, through interfaces (connection devices), the control panel reacts to signals from daylight and occupancy sensors in a preprogrammed fashion to switch and dim certain lights. Window-shade control is two-way: shading devices may close automatically when direct solar radiation is detected in a specific area (while also causing lighting to brighten) or they may open when direct sunlight is absent (but useful daylight is abundant). In addition, a conference room arranged for audiovisual display may provide control of lighting and shades via a local lectern-mounted, scene-preset controller, and so on. When another stand-alone system such as a fire alarm system (which itself may be part of an overall security/safety system) sends an emergency signal, the control panel reacts as programmed. It may turn on all lighting to full output, or it may brighten exit paths and dim other lighting, and so forth. This interconnection between two stand-alone systems is characteristic of a BAS.

31.28 BUILDING AUTOMATION SYSTEMS

The clear trend in buildings, except for small or simple structures, is to use integrated system design plus centralized monitoring and control of



(a) (b)

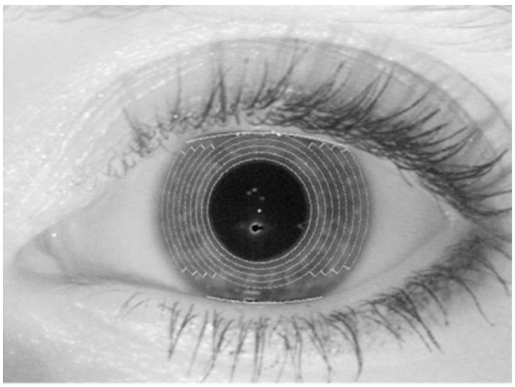
Fig. 31.22 Stand-alone electronic locking system. (a) The arrangement and interconnection of equipment at each portal are shown. The card reader (swipe or insert type) is built into the door mechanism, which also contains the electric strike mechanism. (b) Each lock (swipe style on the left and insert type on the right) is individually programmed using the laptop computer seen in the background. Each lock can be programmed for up to 1500 users, each on a time-schedule basis, covering not only working hours, holidays, weekends, and the like, but also individual time schedules. All programming is performed locally, and the passage record of each lock can be downloaded easily. (Courtesy of Ilco-Unican Corp., Electronic Access Control Div.)

building systems. The subsystems almost always included in a building automation system (BAS) are HVAC, energy management, and lighting control. Inclusion of security, life safety (fire alarm, fire control and suppression, plus emergency aspects of vertical transportation), material handling, and some aspects of communications depends upon the specific needs of the building. This trend toward building automation, which previously was economically justifiable only in large owner-user facilities, is today not only economically feasible but also very nearly an economic necessity because of high labor costs and the relatively low cost of computer and microprocessor controls. What the rapid advances in microelectronics and computer technology have done is to make possible and practical detailed multipoint monitoring and control in real time, the result of which (assuming proper programming and BAS operation) can be a highly efficient, environmentally conscious, and money-saving facility. Indeed, the advantages of such an arrangement are so great that retrofitting of existing buildings, which is more costly than new construction, has become a major industry.

Fig. 31.23 This foolproof identification procedure relies on the fact that no two persons have identical retinal vascular patterns. The illustrated device, usually placed at an unmanned controlled-access portal, scans the entrant's retina, compares it to a previously recorded pattern, and then either permits or denies entry. (Photo courtesy of Eyedentify Inc.)

Because the technique of building automation has grown so rapidly in the past few years, the terminology surrounding it and its equipment suffers from a lack of standardization and uniformity. Thus, terms such as *building automation, intelligent buildings, computerized building control, integrated computer control, supervisory data systems,*

(a)



(b)

Fig. 31.24 *Iris-scanning system. (a) When the system is used as an access control device at a portal, the entrant stands about 10 to 12 in. (250—300 mm) away from the scanner as the iris is scanned. The technology relies on the fact that each person's iris has unique and randomly formed features. (b) After scanning, the image is digitized (as shown) and compared to a computer record. The entire procedure is very fast; entry access or denial is automatic. (Courtesy of IriScan Inc.)*

Fig. 31.25 *This biometric identification device takes more than 90 hand measurements that are then converted into a unique identification "template" that is stored in the system's computer. Once identification is made, it can be used for access control. Access points can be programmed to permit entry to authorized personnel on any time/date schedule desired.*

integrated building control, *facilities management systems*, and so on are used almost interchangeably. The expression *building automation system* is used in the discussion that follows. Every BAS is by definition programmed; thus, any discussion necessarily involves basic control and computer terminology, in addition to that which specifically applies to a BAS. A short glossary should prove helpful in this regard.

31.29 GLOSSARY OF COMPUTER AND CONTROL TERMINOLOGY

Address. A number used to identify an I/O (input/output) channel or a module.

Algorithm. A detailed description, often in flow-diagram or mathematical form, of a method for solving a problem. The outline used for computer or microprocessor programming.

Alphanumeric. Characters including letters of the alphabet, symbols, and numbers.

Analog data. Numerical information about physical variables given in a physically representative, continuously variable form (as with dial meters, temperature gauges).

Artificial intelligence. A branch of computer science concerned with computer programs that "learn" on the basis of experience and modify their own behavior accordingly.

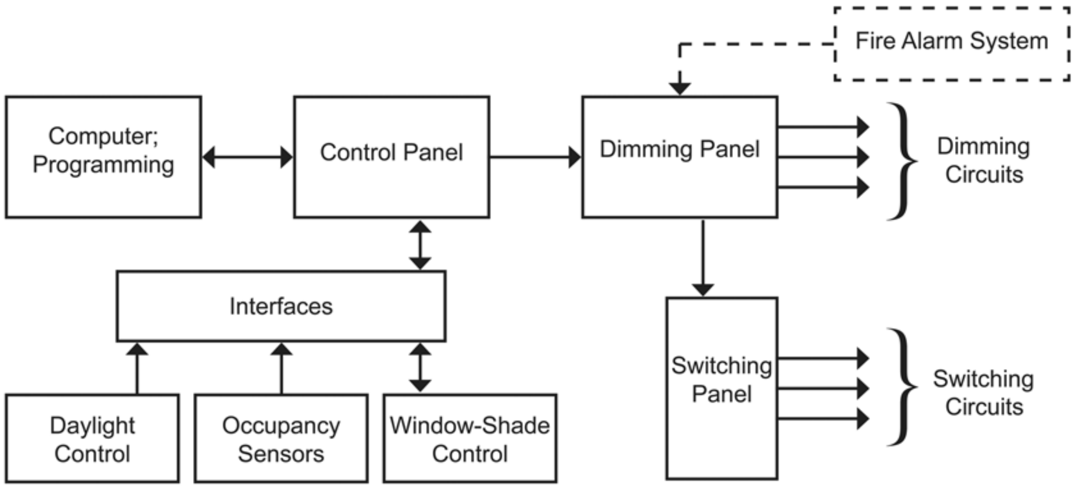


Fig. 31.26 *Block diagram of a typical stand-alone automated lighting control system. A connection to another stand-alone system (fire alarm), shown dotted, would exist at the overall building control level.*

ASCII. A 7-bit standard alphanumeric code established by the American National Standards Institute (ANSI). The acronym ASCII stands for American Standard Code for Information Interchange.

Baud. Rate at which information is transmitted (in bits per second).

Binary. A numeric system using only 1 and 0, normally used to represent the on and off circuit conditions.

Bit. The number 1 or 0; a contraction of *binary digit*.

Building automation system (BAS). Buildingwide, a computer-based system that monitors and controls selected aspects of building operations. A BAS is understood to include all of the equipment involved and its interconnections.

Bus. An electrical data channel.

Byte. A string of bits; 8 bits unless otherwise specified.

Central processing unit (CPU). That portion of a computer, microprocessor, or programmable controller that processes data and executes programs; the "brains" of a computer.

Converter. General term for a device that converts data or energy from one form to another. Data converters are analog to digital (ADC) or digital to analog (DAC). Energy-form converters (e.g., temperature or illuminance to voltage) are properly called *transducers*.

Digital data. Data in digital form, usually binary.

Direct digital control (DDC). Control arrangement that processes digital input data according to a programmed algorithm and yields a control function (e.g., the action of a local microprocessor controller or a computer control function).

Duplex, duplex transmission. Simultaneous bidirectional data transmission.

EIA. Electronic Industries Alliance (formerly Electronic Industries Association). Establishes data communication standards (e.g., RS-232).

Energy management system (EMS). Computer-based system for monitoring and controlling facility energy use. Frequently part of a BAS.

Hardware. All physical equipment associated with a computer or control system, as opposed to software.

I/O. Input/output.

LCD. Acronym for liquid crystal display.

LED. Acronym for light-emitting diode.

Load control, load management. Arrangement whereby energy-using devices are monitored and controlled. Part of an EMS.

Local area network (LAN). Signal network providing intercomputer communications.

Logic. Factors involved in the design of a CPU (or control scheme).

Microprocessor. A CPU, usually in the form of a single integrated circuit (IC), preprogrammed to perform specific functions in response to specific input.

Modem. Device that connects a data-originating device to a communication line; from *modulator–demodulator*.

Multiplex(er) (MX, MUX). Use of a single communications line for simultaneous transmission of multiple signals.

Nonvolatile memory. Memory that remains intact when electric power is shut off.

Operating system. Software that controls input to, output from, and operation of the CPU.

Parity. Method of verifying the accuracy of recorded data.

Point. General term used to describe either a sensor/monitor location or a specific control signal in a BAS.

Port. An I/O connection point.

Programmable controller. Electronic device containing a microprocessor, a programming means or device, and I/O interfaces.

Protocol. Conventions governing the format and timing of signaling between communication devices (e.g., between computers in area networks).

RAM, ROM, PROM, EPROM. Random access memory, read-only memory, programmable ROM, erasable PROM.

Real time. Arrangement in which a computer receives and processes data without introduction of any deliberate time delay (effectively providing an immediate response).

RS-232. Standard for interconnecting digital communications devices, such as computers, printers, and monitors.

Software. Computer program; as opposed to hardware.

Stand-alone. Descriptive term for a control device or system that can perform independently and usually can also interconnect as a subsystem (controller) in a larger system.

UPS. Uninterruptible power supply.

Volatile memory. Memory that loses its information on loss of power.

Word. A group of bits that is treated as a single unit.

31.30 BAS ARRANGEMENT

A block diagram of a typical BAS is given in Fig. 31.27. Notice that information is transferred *vertically* between levels within a stand-alone system, whereas *horizontal* intersystem information transfer occurs only at the highest level (level 1), because that is the level at which systems are interconnected. (In practice, some interconnection also occurs at level 2.) This means that a smoke alarm from level 5 of the fire alarm system travels to level 1, where the central controller tells the other stand-alone systems to take the required action. These systems in turn then signal downwards, essentially to level 4, where appropriate commands are given to controls for supply fans, elevators, security, and so on. The stand-alone systems are essentially independent, and in practice cannot easily be interconnected because of the absence of standardization in wiring and computer protocols. The ostensibly simple problem of connector standardization has yet to be fully solved, as anyone who has done hands-on work in the communication field can attest, although the situation is much improved over the near chaos that once reigned. Buildings with fully or even partially integrated systems are not as common as might be suspected. Such buildings may reasonably be called "intelligent buildings" and are discussed in the next section.

Returning to the block diagram (Fig. 31.27) of a typical BAS: Any specific BAS may contain more or fewer monitors, sensors, dependent and stand-alone local controllers, and interconnected systems, but the overall arrangement remains generally the same. Actually, depending upon the equipment manufacturer and the system complexity, some of the functions and levels can be telescoped or grouped. Our discussion deals with the general case. To solidify the discussion, fire control and evacuation system terminology is used as a relatively simple and straightforward example of overall system design, function, and interconnections.

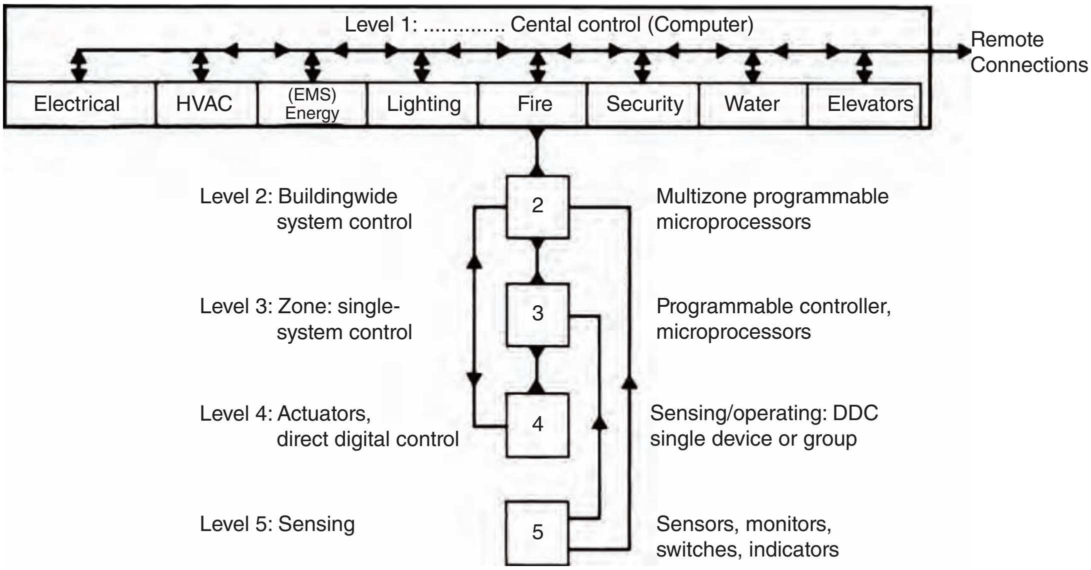


Fig. 31.27 *Overall block diagram of a building automation system (BAS). In an actual system, the various levels and devices can be combined and telescoped by use of equipment that combines several level functions in a single housing.*

Level 5 in the diagram is the lowest system level. It contains automatically operated passive sensors such as flame, smoke, ionization, temperature, and water-flow detectors; physical condition indicators such as smoke damper and fire-door position sensors; and manual fire alarm pull stations. All yield a digital signal (on–off), which is transmitted to level 3. As level 5 is purely a sensor/monitor level, it does not receive any control or operating signals.

Level 4 contains sensor/operators or actuators (i.e., devices that both transmit a condition signal and receive an operation signal). In our example, this level could contain smoke damper and fire-door actuators, smoke vent controls, sprinkler system valves, and fan control (override) switches. The last item can either reside at this level or can be controlled through the HVAC system via level 1, 2, or 3. Control at this level would typically involve hard-wiring of a single device or block.

Level 3 could represent a floor, zone, or area controller, with either relay circuitry or microprocessor control (programmable controller), depending upon system complexity. This level receives information from levels 4 and 5, processes it, returns control information to level 4, operates specific local audible and visible alarms directly, and sends alarm and condition information to the level-2 building controller and to the master controller (computer) at level 1. It also receives and processes signals from levels 1 and 2, containing such information as alarm reset, alarm device operation for building emergency evacuation, and any reprogram or reset function.

Level 2 contains the building's central fire and evacuation system (life safety system) controls. This level can contain some of the level-1 programming logic relating to firefighter control of elevator operations and HVAC fan functioning, or it can simply act as an I/O device to level 1 for these functions, again depending upon system design and complexity. In some facilities, these life safety system functions may be controlled from a separate console that is interconnected with the BAS. In a multibuilding facility, this level contains the individual building fire system central control and interconnections to other building fire system controllers, as well as external connections for city alarm and external supervisory services.

Level 1 is the central computer console. This level receives status reports on the individual devices from level 4 or 5; on areas, zones, and subsystems from level 3; and on the entire fire/evacuation system from level 2. Hard-copy printouts of all alarms and periodic status reports are generally made at this level, although they can

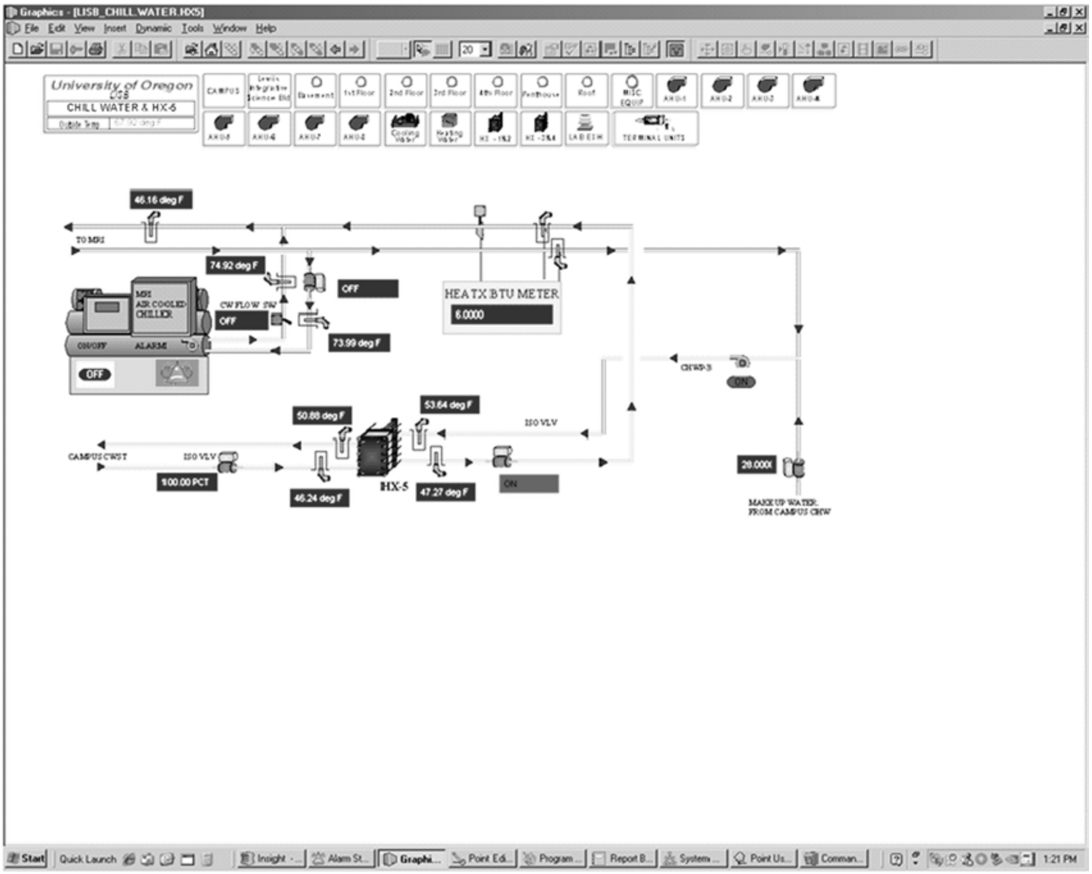


Fig. 31.28 *Screen shot of a portion of a building system and the status of all components. Here we see the chiller status (on–off, COP, tons, run time), water temperature and flow in supply and return lines, and condenser water temperature. (Courtesy of Fred Tepfer.)*

also be made at level 2. Computer monitors at level 1 can be used to view the status of any area and all the devices in the fire/evacuation system, or for any other system (Figs. 31.28 and 31.29), either graphically or as a table. Pictorial graphics for nontechnical end users are also possible. At level 1, information is transferred to HVAC, elevator, security, and lighting systems in preprogrammed alarm modes, with manual override possible. A fire emergency scenario might interconnect with the HVAC, elevator, security, water, electrical, and lighting systems to activate exhaust and pressurizing fans and deactivate supply fans, place elevators in fire-evacuation mode, override access barriers to permit unhindered facility evacuation, connect fire pumps to emergency power feeders, disconnect high-voltage feeders, and activate emergency lighting, all via preprogrammed intersystem functions. The system operator at level 1 could then view any part of any system and reactivate or override preprogrammed functions as desired. With this system design, this is the level at which human supervisory intervention is intended. At other levels, such intervention occurs only if trouble arises, periodic maintenance is scheduled, or an alteration is required.

Returning to Fig. 31.27, we can consider a much more complex nonemergency system: energy. Here, level 5 senses and continuously monitors indoor and outdoor temperature and humidity, duct air temperatures, space pressurization, airflows, and the operating and load status of all fans, compressors, and refrigeration devices. Level 4 contains monitors and direct digital controls for valves, boilers, chillers, fans,

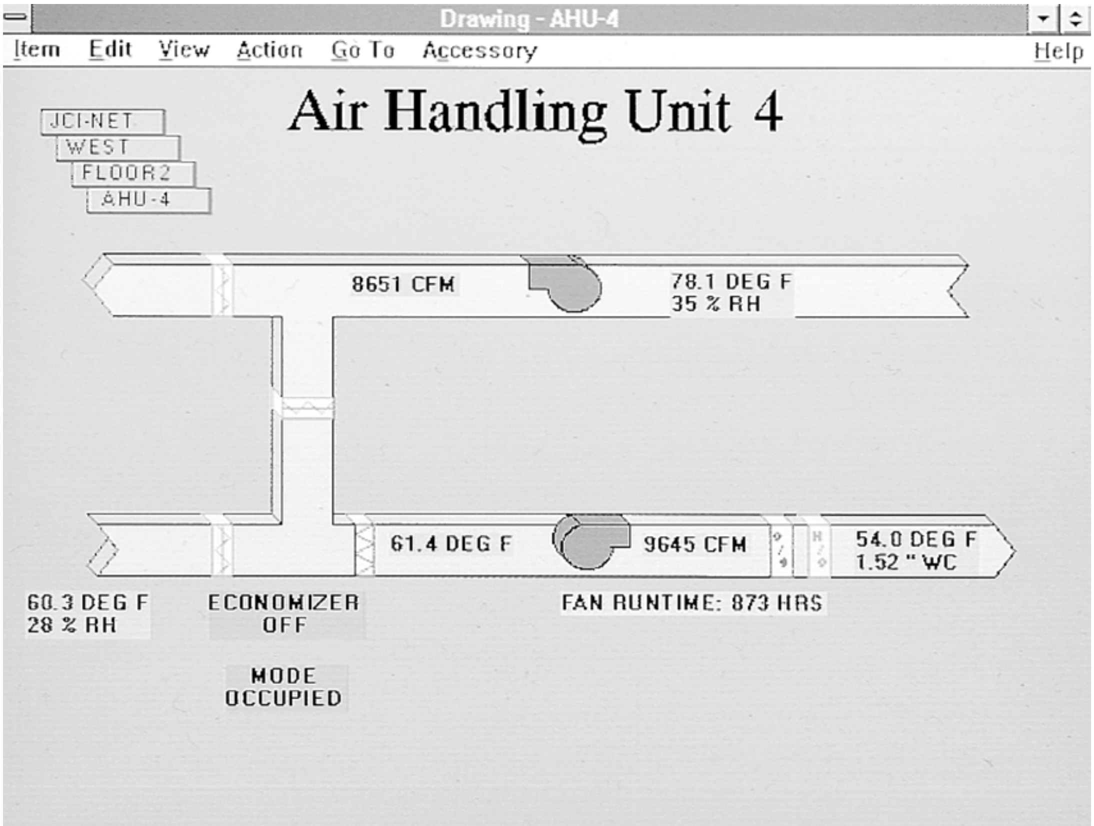


Fig. 31.29 *A workstation screen can display any portion of any system in the BAS. Here an air-handling unit (AHU) is displayed with data on airflow, air temperatures, and relative humidity in each duct section. In addition, cumulative fan run time, economizer status, and area occupancy status are displayed. (Redrawn by Tyler Mavichien from source: Johnson Controls.)*

humidifiers, dampers, cooling towers, and compressors. Levels 2 and 3 contain electric load managers for duty cycling and demand limiting, HVAC controls for economizers, run-time optimizers, supply air and supply water reset, chilled and condenser water reset, enthalpy switching, load sequencing, and the like. These functions are performed either by a stand-alone EMS controller (see Fig. 27.15) or by individual demand, HVAC, and chiller load managers controlled by level-1 logic. Finally, level 1 contains the programming for all of the foregoing functions, any of which can be displayed at a level-1 workstation terminal at any time. The system operator can then reprogram any function after analyzing system performance at the level-1 computer and obtain immediate visual and hard-copy readout of the changes.

31.31 INTELLIGENT BUILDINGS

Although the term *intelligent building* seems to attribute a decidedly human capability to an inanimate object, the term's meaning (as defined by the Intelligent Buildings Institute in 1987) is, "a building which provides a productive and cost-effective environment through optimization of its four basic elements—structure, systems, services, and management—and the interrelationships between them. . . . Optimal building intelligence is the matching of solutions to occupant need." In the framework of such a definition, the intelligence of a building depends upon the ability of the design team to understand the occupants' present needs (via a current Owner's Project Requirements document) and to make an educated forecast of the client's and occupants' future needs. Because a building's useful life depends largely upon the accuracy of this forecast, building systems are being designed with open control architecture that lends itself easily and economically to change, both minor and major. The term *open architecture* is generally understood to mean, in terms of a BAS, a system design that, at the very least, can do the following:

- Utilize equipment from any manufacturer whose equipment meets industry-wide specifications
- Readily reprogram equipment to serve a variety of functions
- Supply required system information at any I/O port
- Permit access to databases at any workstation
- Utilize networks for information transfer at one or more levels

These requirements demand open protocols, standardized transmission media and connectors, and virtually unlimited cabling space. (The last requirement is easily fulfilled by using any of the underfloor or cellular floor raceway systems described in Chapter 28.) At this writing, proprietary interests and the prevalence of stand-alone system design are retarding the move to open architecture in the United States, whereas it is being adopted rapidly in Asian mercantile centers. There is movement toward standardization, however, as seen in the development and application of protocols such as BACnet (ASHRAE).

Referring to Fig. 31.27, which shows a prevalent BAS architecture, an open system would eliminate at least two of the levels, reducing the system to a three-level structure that *might* be structured as follows:

1. *Level 1,* the uppermost level, contains workstations connected to a main data bus. This level, which might be called the *management* or *information level*, has direct access to databases and information networks. It serves to establish operational programming and procedures. All points are accessible from any workstation.
2. *Level 2,* the intermediate level, might be called the *supervisory* or *network level*. Network controllers serve as a network platform—both supervising stand-alone controllers from various systems at the third level and transferring information to other network controllers supervising other areas of the building via

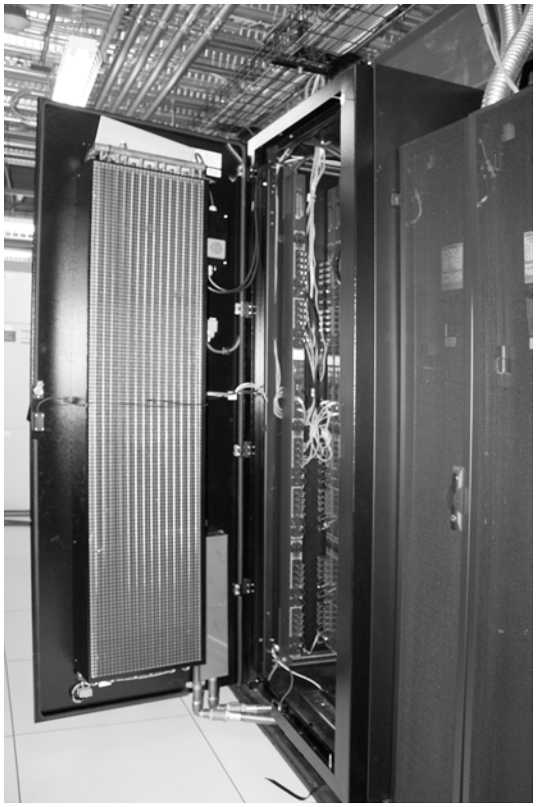


Fig. 31.30 *Network control unit acts as a LAN platform, performing supervisory functions for a portion of a building. It connects to operator workstation(s) at the upper management level, to other network controllers at its level via the LAN, and to specific stand-alone controllers at the lower, control level. This modular server rack has radiant cooling.*

Fig. 31.31 *Fire control unit. This device controls intelligent addressable analog devices in an intelligent fire control system. (Courtesy of Johnson Controls.)*

Fig. 31.32 *A unitary controller is designed to control single-zone HVAC subsystems such as heat pumps, fan-coils, and the like. It is preset from the network level but can also be locally monitored and adjusted to satisfy local requirements. These adjustments are made with a portable plug-in control unit. (Courtesy of Johnson Controls.)*

the LAN. In addition, the network controllers exchange information with one or more workstations. A network controller can also act as a process controller. A typical unit might appear as in Fig. 31.30. Energy-efficient cooling of high-density computer installations is an emerging problem.

3. *Level 3,* the control level, contains dedicated controllers in stand-alone systems. The units are highly flexible and can be locally reprogrammed to control the same function in a wide variety of different systems. Two such controllers are shown in Figs. 31.31 and 31.32.

31.32 INTELLIGENT RESIDENCES

The operational principles of remote control and automation discussed previously in this chapter, and also in Chapters 27 and 16, have found ready application in residential automation and control equipment. Residences so equipped and variously referred to as *intelligent*, *smart*, or *automated homes* appear increasingly in the real estate press. The degree of automation in these houses varies considerably, the simplest being no more than a low-voltage control system of the type described in Section 27.32, with time-based programming using a relatively simple microprocessor. More complex systems use a touch-screen computer for control or a portable plug-in programmable microprocessor to set various portions of the system. The best (and most expensive) systems achieve a level of user–system integration not yet available in a complex BAS, in that the user's telephone can control any portion of the system directly. This is possible because only one level or, at most, two levels of control are involved—that is, the commands are on/off/set, where the last refers to a particular electronic contact. This contact in turn establishes a new preprogrammed condition such as night-setback, lighting preset for extended absence, reset of second-floor temperatures to daytime levels, and so forth. These systems also allow relatively straightforward reprogramming to meet the occupant's specific needs.

Because all new residential construction includes some degree of automation that will surely increase in the future, all residences, both single and multiple, should be provided with the cabling and/or raceway system that is the backbone of any automation system. At this writing, the cost of plastic optical cable (POC) is approximately competitive with copper cabling in large quantities. The decision as to what cabling and distribution system to install is technical and economic. At the very least, every room in a residence should be equipped with audio/video/control point outlets. In addition, a study, a recreation room, and at least one bedroom should be wired as potential fully equipped home offices. This applies not only to anticipated automation wiring, but also to power outlets and lighting.

BUILDING PHYSICAL SECURITY

Although not directly related to "signal systems," the issue of physical security for buildings is an escalating concern for a wide range of building types and clients. It is beyond the scope of this book to address this problem in any detail; however, it should be mentioned that the design of mechanical and electrical systems for a "secure" building will involve considerations beyond those seen in a typical design situation. Resources to assist system designers in these circumstances may be found at FEMA (2013) and DHS (2013).

References and Resources

ASHRAE. 2012. Standard 135, *BACnet – A Data Communication Protocol for Building Automation and Control Networks*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

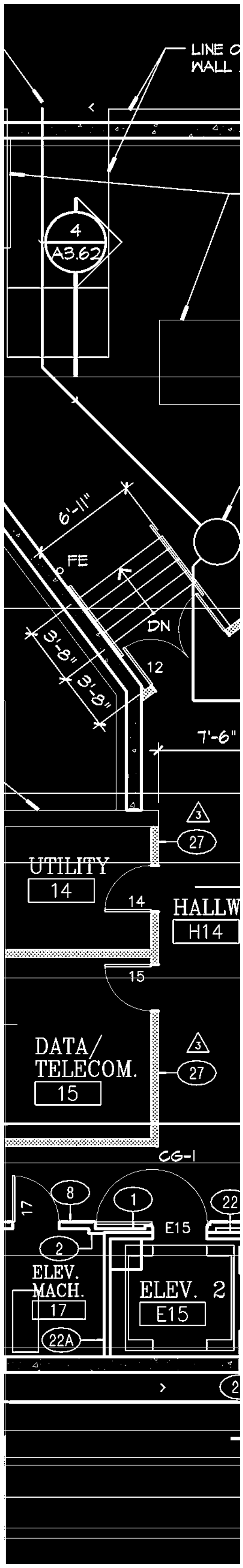
Automated Buildings. http://www.automatedbuildings.com/

DHS. 2013. *Building and Infrastructure Protection Series: Designing Buildings to Withstand Almost Anything*. Department of Homeland Security. http://www.dhs.gov/building-and-infrastructure-protection-series-designing-buildings-withstand-almost-anything

FEMA. 2013. *Building Design for Homeland Security*. Federal Emergency Management Agency. http://www.fema.gov/media-library/assets/documents/4655?id=1939

PART IX

TRANSPORTATION



No systems in a multistory structure are taken for granted more consistently than elevators and escalators, which are relied upon to move people quickly and safely under all conditions, including emergencies. This movement should be rapid, trouble-free, and economical. Furthermore, because vertical transportation accounts for 10% to 15% of the construction budget in tall buildings, somewhat less of the building area, and somewhat more of the operating cost—and is a determining factor in building shape, core layout, and lobby design—elevator and escalator selection and design integration are major tasks for the architectural designer.

Chapter 32 introduces the subject with a description of components including traction equipment, cars, safety devices, and systems of control and supervision. Fundamental topics, such as codes and standards and requirements for the disabled, are also covered. Criteria are established for elevator performance, and extensive car performance data are presented that can be used in conjunction with design criteria to select the size, number, and speed of elevators to meet design intent and criteria. Principles of elevator zoning are presented. The chapter continues with an analysis of spatial requirements for elevators, including shafts, lobbies, and core arrangements, and concludes with special considerations such as energy use, safety, security, and noise.

Chapter 33 addresses special-case elevators: freight elevators, nonvertical designs, residential elevators, and chair lifts, with a discussion of equipment, capacities, selection, economy, and comparison (where applicable) to conventional design. The chapter also covers interesting design options including double-deck cars and observation cars. Chapter 33 also describes material-handling devices: dumbwaiters, horizontal and vertical conveyors, pneumatic systems, container delivery systems, and automated self-propelled vehicles. This information responds to the need to plan for material handling in commercial and institutional buildings, rather than treating the subject as an afterthought—with resultant inefficiency, overloading of freight facilities, and misappropriation of passenger elevators.

Chapter 34 explains escalator system components, capacities, sizes, speeds, and methods of selection, followed by special topics including lighting, fire protection, power/energy requirements, and budget estimating. Information on mechanized walkways and ramps is also presented.

CHAPTER 32

Vertical Transportation: Passenger Elevators

GENERAL INFORMATION

32.1 INTRODUCTION

OF THE MANY DECISIONS THAT MUST BE made by the designer of a multistory building, probably none is more important than the selection of the vertical transportation equipment—that is, the passenger, service, and freight elevators and the escalators. Not only do these items represent a major building expense, being in the case of a 25-story office building as much as 10% of the construction cost, but the quality of elevator service is also an important factor in a tenant's choice of space in competing buildings.

Although the final decision as to the type of equipment rests with the architect, the factors affecting it are so numerous that the building designer should consult with an elevator expert. This service is available from consultants in the field and from the major elevator and escalator manufacturers. The function of this chapter is to familiarize the architect and engineer with the nature and application of vertical transportation equipment in order to enable them to make preliminary design decisions and interact effectively with consultants.

32.2 PASSENGER ELEVATORS

This chapter is concerned primarily with general-purpose traction and hydraulic elevators.

Ideal performance of an elevator installation will provide minimum waiting time for a car at any floor level; comfortable acceleration; rapid transportation; smooth, rapid braking; accurate automatic leveling at landings; and rapid loading and unloading at all stops. The elevator system must also provide quick, quiet operation of doors; good floor status and travel direction indication (both in the cars and at landings); easily operated car and landing call buttons (or other devices); smooth, quiet, and safe operation of all mechanical equipment under all conditions of loading; comfortable lighting; reliable emergency and security equipment; and a generally pleasant car atmosphere.

In addition to passenger-satisfaction service considerations, elevators have architectural design impacts. Cars and shaftway doors must be treated in a manner consistent with the architectural unity of the building. More important, however, elevator shaftways are major space elements whose integration into a building is a prime factor in composition, as is the design of the elevator lobby.

32.3 CODES AND STANDARDS

Perhaps more than any other element of construction, elevators are governed by strict installation codes. The definitive resource in the United States is the American Society of Mechanical Engineers' ANSI/ASME Standard A17.1, *Safety Code for Elevators and Escalators*. The code has legal force in most parts of the United States. Two related standards should be noted. ANSI/ASME Standard A17.3 covers existing elevators and escalators, and Standard A17.4 covers emergency evacuation of passengers from elevators. Some states and municipalities have their own elevator codes (Massachusetts, Wisconsin, Pennsylvania, New York City, Seattle, and Boston, among others) that are generally based upon, but more stringent than, the ANSI/ASME code.

In addition to the elevator code, other construction and installation codes influence elevator work. NFPA 101, the *Life Safety Code* (from the National Fire Protection Association), details certain fire safety requirements; NFPA 70 (the *National Electrical Code*) governs some of the electrical aspects of elevator construction; and state and local laws can add a multitude of requirements and restrictions bearing on fire safety, emergency power, security concerns, and special accommodations for persons with disabilities. Provisions for the disabled are specifically covered by ANSI A117.1 (*Accessible and Usable Buildings and Facilities*, a special industry code from the American National Standards Institute), by the requirements of the Americans with Disabilities Act (ADA), and, in most locations, by local law. Like most large industries, the elevator industry is self-regulating and standardized. The National Elevator Industry, Inc. (NEII) publishes standard elevator layouts for traction and hydraulic installations. Elevator consultants and elevator company representatives are normally knowledgeable about all of the codes and standards in force, but this does not relieve the architect-engineer of legal responsibility for the design. Therefore, we strongly recommend that in the preliminary planning stage all pertinent regulations concerning vertical transportation be acquired, reviewed, and understood.

TRACTION ELEVATOR EQUIPMENT

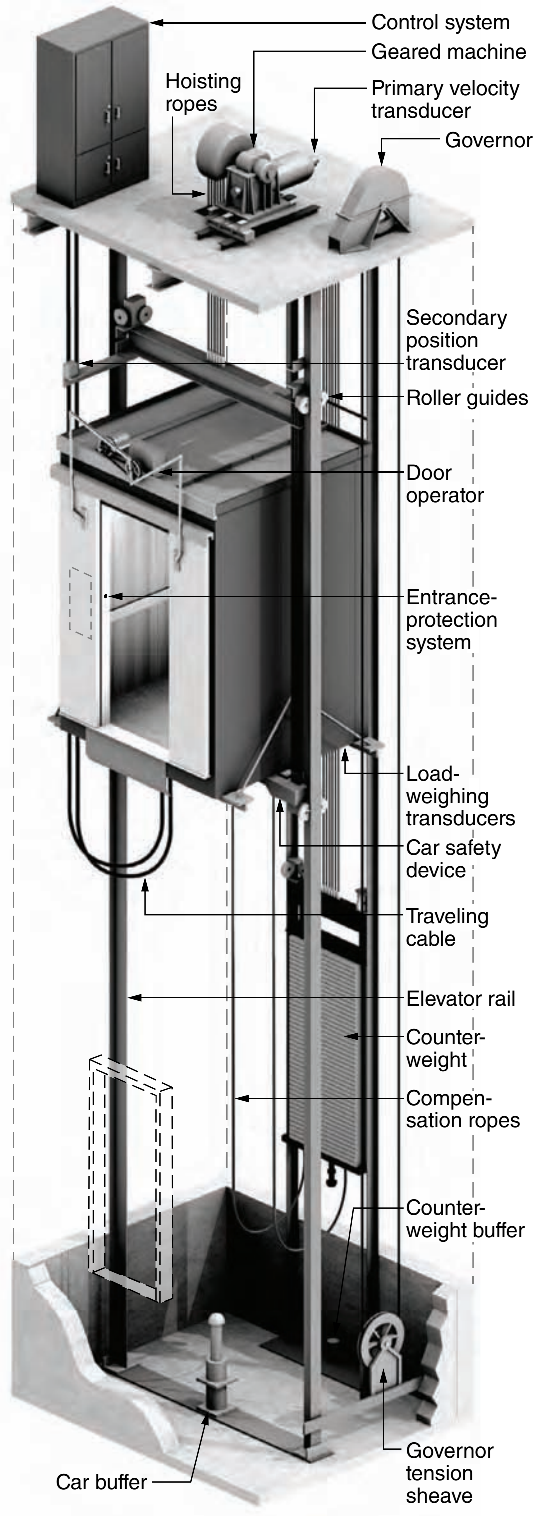
32.4 PRINCIPAL COMPONENTS

The car, cables, elevator machine, control equipment, counterweights, hoistway, rails, penthouse, and pit are the principal parts of a traction elevator installation. An idea of the functioning and orientation of these items of equipment can be obtained from Fig. 32.1.

The car is the only item with which the average passenger is normally familiar. Some of a building's prestige depends upon proper design of the elevator car. Essentially, the car is a cage of some fire-resistant material supported on a structural frame, to the top member of which the lifting cables are fastened. By means of guide shoes on the side members, the car is guided in its vertical travel in the shaft. The car is provided with safety doors, operating-control equipment, floor-level indicators, illumination, emergency exits, and ventilation. It is designed for long life, quiet operation, and low maintenance.

The cables (ropes) that are connected to the crosshead (top beam of the elevator) and carry the weight of the car and its live load are made of groups of steel wires specially designed for this application. Four to eight cables, depending on car speed and capacity, are placed in parallel. Although multiple ropes are used primarily to increase the traction area on the drive sheaves, they also increase the elevator safety factor—as each rope is normally capable of supporting the entire load. The minimum factor of safety varies from 7.6 to 12.0 for passenger elevators and from 6.6 to 11.0 for freight elevators. The cables from the top of the car pass over a motor-driven cylindrical sheave at the traction machine (grooved for the cables) and then downward to the counterweight. Innovative coated cables are resulting in reduced energy consumption with no reduction in safety.

The counterweight is made up of cut steel plates stacked in a frame attached to the opposite ends of the cables to which the car is fastened. It is guided in its travel up and down the shaft by two guide rails typically installed on the back wall of the shaft. Its weight equals that of the empty car plus



Interactive Animation

Fig. 32.1 *Components of a geared elevator installation with solid-state control and motor drive. (Courtesy of Otis Elevator Co.)*

40% of the rated live load. It serves several purposes: to provide adequate traction at the sheave for car lifting, to reduce the size of the traction machine, and to reduce power demand and energy cost. These advantages come at the cost of having to strengthen the overhead machine room floor, which must carry the additional structural load of the counterweight.

Approximately 75% of the energy expended in lifting a car is returned to the system by regeneration when the car is lowered. Regeneration is the process by which the traction motor becomes a *generator* when the car is lowered and feeds power back into the electrical system. The unrecovered energy appears as heat, primarily in the machine room. See Section 32.43 for a discussion of traction elevator system energy requirements.

To compensate for the hoist rope weight, which becomes an important factor in high-rise elevator installations, cables are attached to the bottom of the car and the counterweight, thus equalizing loads regardless of the car position. These cables can be seen in Fig. 32.1.

The elevator machine turns the sheave and lifts or lowers the car. The machine consists of a heavy structural frame on which are mounted the sheave and driving motor, the gears (if any), the brakes, the magnetic safety brake, and certain other auxiliaries. In many existing installations, the elevator driving (traction) motor receives its energy from a separate motor-generator (m-g) set, which is in operation during the period that the particular elevator is available to handle traffic. This m-g set is properly considered a part of the elevator machine, although it may be located some distance from it. In newer installations, solid-state power and control equipment will replace the m-g set. A governor, which limits the car to safe speeds, is mounted on or near the elevator machine.

The control equipment is usually divided into three groups:

1. *Drive (motion) control* is concerned with the velocity, acceleration, position determination, and leveling of the car.
2. *Operating control* covers car door operation and functioning of car signals, including floor call buttons and all indicating devices.
3. *Supervisory control* is concerned with group operation of multiple-car installations.

The actual physical devices in these control systems were historically electromechanical, but solid-state devices are used in modern installations. The indicating and control devices that are seen by the elevator user, including car and hallway buttons, lanterns, and audible devices, are all coordinated into an overall operational control scheme, to provide rapid, safe, and comfortable vertical transportation.

The *shaft*, or *hoistway*, is the vertical passageway for the car and counterweights. On its sidewalls are the car guide rails and certain mechanical and electrical auxiliaries of the control apparatus. At the bottom of the shaft are the car and counterweight buffers. At the top is the structural platform on which the elevator machine rests. The elevator machine room (which may occupy one or two levels) is usually directly above the hoistway. It contains the traction machine and the solid-state control (or m-g set) that supplies energy to the elevator machine and control equipment. Machinery and control equipment are designed for quiet, vibration-free operation.

32.5 GEARLESS TRACTION MACHINES

A gearless traction machine consists of a DC or AC motor, the shaft of which is directly connected to a brake wheel and driving sheave. The elevator hoist ropes are placed around this sheave. The absence of gears means that the motor must run at the same relatively low speed as the driving sheave. As it is not economically practical to build motors for operation at very low speeds, a gearless machine is utilized for medium- and high-speed elevators—that is, 500 fpm (2.5 m/s) and above. The motors range from 20 to 400 hp (15 to 300 kW).

Gearless machines are generally utilized for passenger service, with car capacities of 2000 to 4000 lb (907 to 1814 kg), although special cars of up to 10,000 lb (4536 kg) have been built. Below 500 fpm (2.5 m/s), geared machines are used. At this writing, maximum car speed is 2000 fpm (10 m/s). Faster drives have been developed and will likely play a role in the development of the next generation of very-high-rise buildings.

A gearless traction machine is considered superior to a geared machine because it is more efficient and quieter in operation, requires less maintenance, and has longer life. The decision as to whether these advantages are worth the additional cost involved can be made only after a careful analysis. Generally, a gearless machine is chosen where the rise is more than 250 ft (76 m), and very smooth, high-speed operation is desired. In the intermediate range of rise and speeds (i.e., 150–250 ft [46–76 m] height and 400–500 fpm [2–2.5 m/s]), excellent equipment, both geared and gearless, is available.

Because virtually every major elevator company operates internationally, and outside of the United States elevator size and speed are specified in kilograms and meters per second, it is useful to be aware of the SI equivalents for key design variables. Because 1 kg is 2.2 lb and 1 m/s is 196.86 fpm, approximate conversion factors of 2 and 200, respectively, can be used (Table 32.1). SI units shown herein are generally the more precise equivalents.

32.6 GEARED TRACTION MACHINES

A geared traction machine has a worm and gear interposed between the driving motor and the hoisting sheave (Fig. 32.2). The driving motor can

TABLE 32.1 Elevator Capacity and Speed, Approximate SI and I-P Product Equivalents

Weight		*Speed*	
Standard SI (kg)	**Approximate U.S. I-P (lb)**	**Standard SI (m/s)**	**Approximate U.S. I-P (fpm)**
1000	2000	1.0	200
1250	2500–3000	1.6	300
1600	3500	2.0	400
2000	4000	2.5	500
		3.15	600
		4.0	800
		5.0	1000

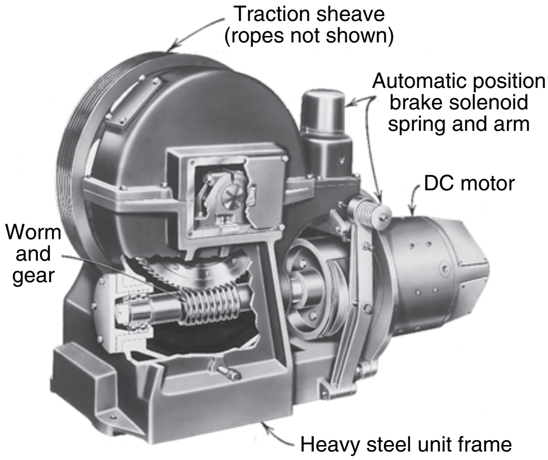


Fig. 32.2 *Cutaway of a typical DC geared traction elevator machine. Note the grooves for multiple ropes in the traction sheave. (Photo courtesy of Schindler Elevator Corp.)*

therefore be a smaller, cheaper, high-speed unit, rather than the large, low-speed unit required by a gearless installation.

The motor used in a geared installation, as in a gearless one, depends upon the type of drive system and may be either DC or AC. Characteristics of the various drive systems and their application are discussed in detail in Sections 32.15 to 32.18. Geared machines are used for car speeds of up to 450 fpm (2.3 m/s) and a maximum rise of about 300 ft (90 m). With an appropriate drive and control system, a geared traction machine can give almost the same high-quality, accurate, smooth ride as is available from a gearless installation.

32.7 ARRANGEMENT OF ELEVATOR MACHINES, SHEAVES, AND ROPES

The simplest method of arranging vertical travel of a car is to pass a rope over a sheave and counterbalance the weight of the car by a counterweight. Then, rotating the sheave makes the car move up or down and requires very little energy to do so. This is essentially the scheme that is used on a majority of high-speed passenger elevators, as illustrated in Fig. 32.3*a*.

When the four or more supporting ropes merely pass over the sheave (*T*) and connect directly to the counterweights, the lifting power is exerted by the sheave through the traction of the ropes in the parallel grooves on the sheave. This system is referred to as the *single-wrap traction elevator machine*. The function of the sheave (*S*) is merely that of a guide pulley; it is called the *deflector sheave*.

The arrangement shown in Fig. 32.3*b* is called *double-wrap 1:1 roping*. It provides greater traction than the single-wrap arrangement and is used in many automatic high-speed installations.

A 1:1 roping arrangement (Fig. 32.3*a*, *b*, *d*) gives no mechanical advantage. The 2:1 roping

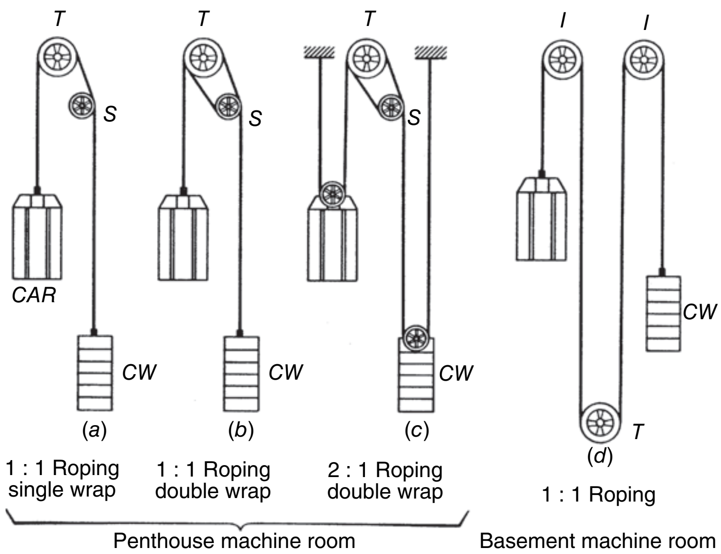


Fig. 32.3 *Elevator roping and sheave arrangements. (a) Basic single-wrap rope arrangement. In (b) and (c), the rope passes over traction sheave* T *and sheave* S*, doubles back over* T*, and then extends past* S *to the counterweight CW. This double-wrap arrangement provides additional traction at the drive sheave. (d) Roping arrangement for a basement machine room.*

(Fig. 32.3*c*) has a mechanical advantage of 2, which permits use of a high-speed, low-power (and, therefore, lower-cost) traction machine. This arrangement is used for a wide variety of installations varying from medium-speed (500–700 fpm [2.5–3.6 m/s]) gearless passenger elevators to low-speed, heavy-duty freight elevators.

In types *a*, *b*, and *c* in Fig. 32.3, the elevator machines are located in a machine room penthouse at the top of a hoistway. If, for architectural or other reasons, it is desired to eliminate the penthouse, a basement machine room can be used with the roping shown in Fig. 32.3*d*. This arrangement uses geared traction equipment with speeds of up to 400 fpm (2.0 m/s). All the illustrated ropings are applicable to the full range of car capacities.

32.8 SAFETY DEVICES

The main brake of an elevator is mounted directly on the shaft of the elevator machine (see Fig. 32.2). The elevator is first slowed by dynamic braking of the motor, and the brake then operates to clamp the brake drum, thus holding the car still at the floor.

A dual safety system, designed to stop an elevator car automatically before its speed becomes excessive, is normally used. The device that acts first is a centrifugal governor or an electronic speed sensor that cuts off the power to the traction motor and sets the brake in the event of a limited overspeed. This usually stops the car. Should the speed still increase, the governor actuates two safety rail clamps, which are mounted at the bottom of the car, one on either side. They clamp the guide rails by wedging action, bringing the car to a smooth stop (Fig. 32.4).

Oil or spring buffers are usually placed in the elevator pit. Their purpose is not to stop a falling car but to bring it to a somewhat cushioned stop if it overtravels the lower terminal. If a car overtravels (down or up), travel sensors deenergize the traction motor and set the main brake. Safety arrangements under emergency conditions (fire or power failure) are discussed in Sections 32.45 and 32.46.

HYDRAULIC ELEVATORS

32.9 CONVENTIONAL PLUNGER-TYPE HYDRAULIC ELEVATORS

The elevators discussed in the preceding sections are traction types; that is, they are raised and lowered as a result of friction that transmits force from the drive mechanism through cables attached to or passing under the car. These cables in turn are raised and lowered by a motor-driven traction

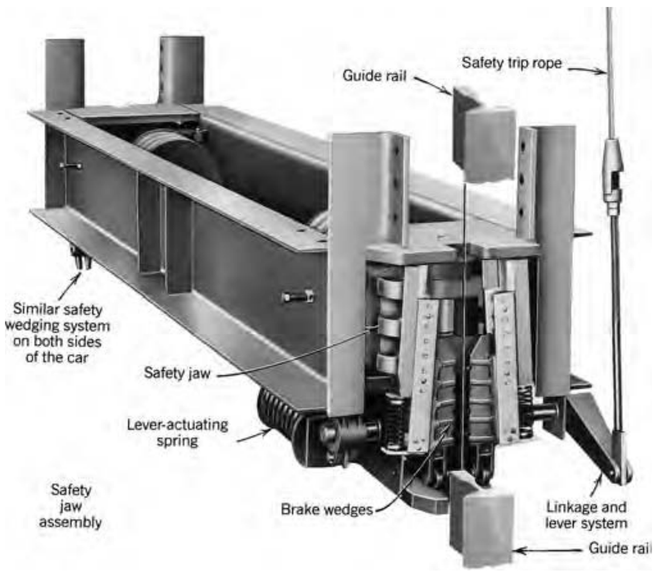


Fig. 32.4 *Elevator safety devices. The governor or velocity transducer senses overspeed, clamping the safety trip rope and releasing the safety jaws, which exert a constant retarding force on the car rails, thus bringing the car to a gradual and safe stop.*

sheave. In contrast, the conventional hydraulic (or plunger) elevator car is raised and lowered by means of a movable rod (plunger) rigidly fixed to the bottom of the car. The absence of cables, drums, traction motors, elaborate controllers, safety devices, and penthouse equipment makes this system inherently inexpensive and often the indicated choice for low-speed (up to 200 fpm [1 m/s]), low-rise (up to 65 ft [20 m]) applications, where construction of the plunger pit does not present difficulties, and/or the absence of a penthouse is desirable.

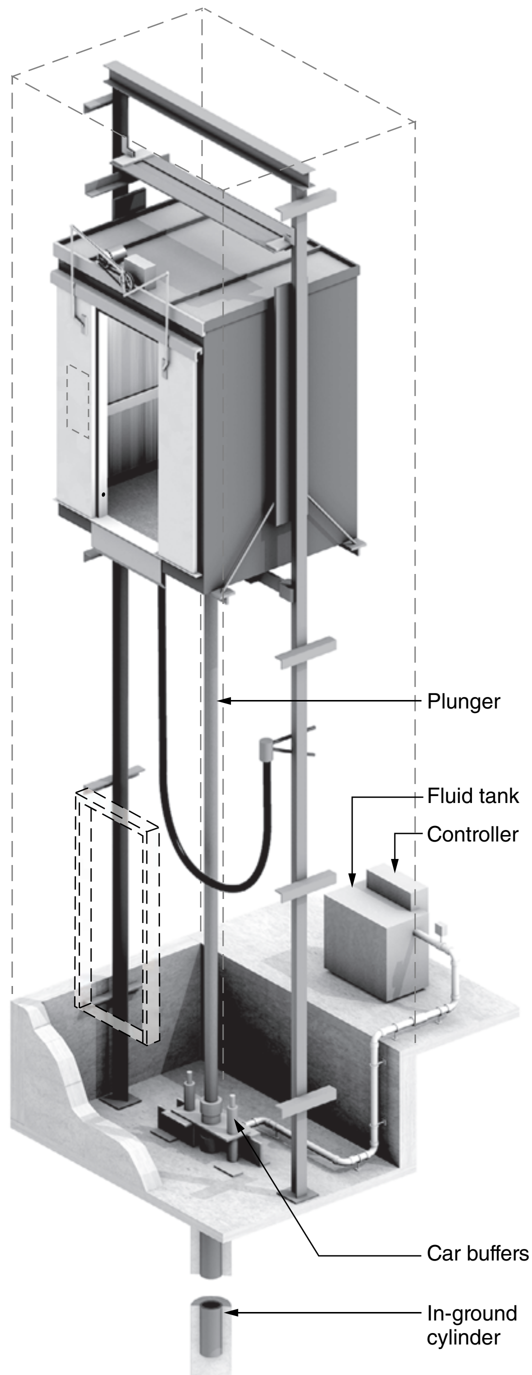
The first hydraulic elevators used water as the system fluid, supplied at sufficient pressure from roof-mounted water tanks. The tanks were kept full by a building's water pumps. All hydraulic elevators today use oil and obtain their motive power from a sealed oil-piping circuit powered by an oil pump.

The components of a typical hydraulic unit are shown in Fig. 32.5. This system operates the same way as a hydraulic automobile jack. Oil from a reservoir is pumped under the plunger, thereby raising it and the car. The pump is stopped during downward motion, the car being lowered by gravity and controlled by the action of bypass valves, which also control the positioning of the car during upward motion. Control systems that are normally used are similar to those for traction elevators—for example, collective and selective collective approaches. Similarly, door arrangements are the same as in traction elevators—that is, single-slide, center-opening, and two-speed arrangements. Automatic leveling is readily available and is standard on all units with automatic controls.

From a design and construction perspective, the major *advantage* of hydraulic units is the absence of an overhead machine room, a penthouse, and traction equipment. As shown in Fig. 32.5, only the guide rails project above the car and, if these are camouflaged, the impression of a freestanding elevator car is given. This effect can be used to good advantage inside large, open spaces such as in shopping malls and stores; when combined with glass-enclosed, observation-type cars, the effect can be striking (see Figs. 32.8).

Additional advantages of hydraulic elevators over traction units include:

- The elevator load is carried by the ground and not by the structure. In contrast, traction units place a large structural load on the penthouse



Interactive Animation

Fig. 32.5 *Phantom view of a conventional "holed" hydraulic elevator, so called because the elevator car rests on a hydraulically activated steel plunger that descends into a hole in the ground. The hole is actually a buried hollow steel cylinder into which oil is pumped, under pressure, to raise the car. The oil pump is inside the fluid tank.*

and machine room floors and on overhead steel as well.

- The hoistway is smaller due to the absence of a counterweight and its guide rails.
- Cars can be lowered manually by the operation of oil valves. This is particularly useful and important in the event of control equipment failure or power outage.
- There is essentially no limit to the load that can be lifted.

The major *disadvantage* of a standard hydraulic elevator is its operating expense. Because it is not counterweighted, it requires a relatively large motor to drive the oil pump, and *all* the energy is lost in heat (see Table 32.2). For an example of this operating cost disadvantage, consider a 3500-lb (1588-kg), 125-fpm (0.6-m/s) hydraulic elevator in a department store. Such a unit requires a 40-hp (30-kW) motor. Assuming the unit to be in operation 10 hours a day, 6 days a week, and assuming a normal 60% time-in-operation figure, analysis shows (remembering that the motor operates only in the up direction):

$$\text{energy used/day} = \frac{40\text{ hp}}{0.82\text{ eff}} \times \frac{0.746\text{ kW}}{\text{hp}} \times 60\% \times 10\text{ h} \times \tfrac{1}{2} = 110\text{ kWh}$$

At an electricity cost of \$0.08/kWh,

$$\text{monthly energy cost} = \frac{110 \times 6\text{ days}}{\text{week}} \times \frac{4.33\text{ weeks}}{\text{month} \times \$0.08} = \$229/\text{month}$$

TABLE 32.2 Comparative Energy Use of Various Motion Control Arrangements

Control Arrangement	Relative Energy Use
Hydraulic elevators	10
UMV motion control; geared DC traction motor	7–7.5
UMV motion control; gearless DC traction motor	6–6.5
Thyristor control; geared DC traction motor	5–5.5
Thyristor control; gearless DC traction motor	4–4.5
Variable-voltage, variable-frequency control, AC traction motor	2.5–3

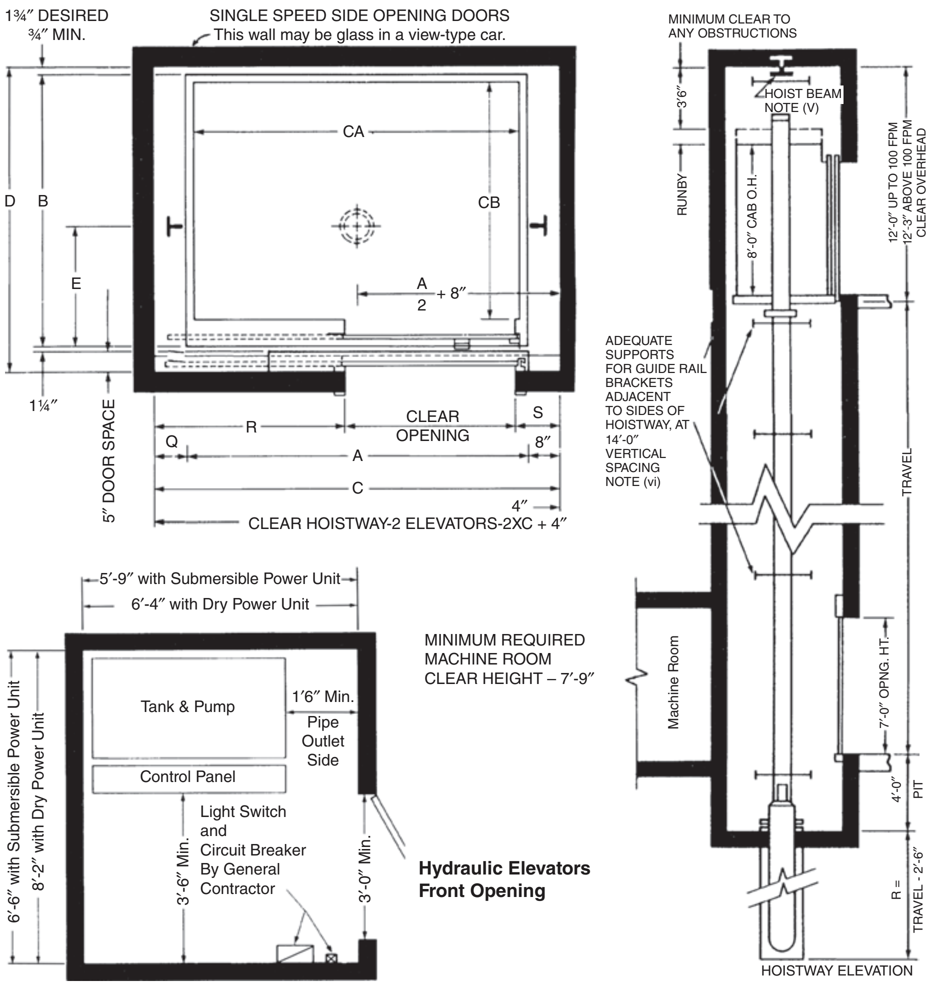
Compare this to the calculated (Section 32.43) monthly energy cost for a 3500-lb (1588-kg), 600-fpm (3-m/s) traction car of \$72 when using solid-state equipment and \$126 with an m-g set power supply, to get an appreciation of the value of a counterweight.

Other *disadvantages* of hydraulic units as compared to traction units include:

- They are limited to low-rise, low-speed applications.
- Ride quality is inferior to that of a good traction unit, although it is entirely acceptable for residential, mercantile, and industrial applications.
- Because oil viscosity changes with temperature, the ambient temperature of the space containing the pump and the oil storage tank must be controlled to maintain ride quality and performance.
- The high inrush current required by the pump each time it starts (which is every time the elevator travels upward) necessitates a "stiff" power supply to avoid problems of flickering lamps and other undesirable line-voltage fluctuations.
- Noise from the pump and motor plus piping noise can be disturbing. This problem can be ameliorated by skillfully locating the pump mechanism (which can be placed up to 50 ft [15 m] from the elevator shaft).

Plunger-type hydraulic elevators have experienced some disfavor because of problems caused by oil seepage into the ground. The plunger travels in a buried steel casing that, despite excellent butyl or other liquid-tight coatings, can corrode after an extended period and leak oil. In most locations, this will violate regulations dealing with groundwater pollution. Because repair of such an oil leak is expensive and entails extended elevator outage, other arrangements (as detailed in the next two sections) have come into increasing use.

Hydraulic elevators are best applied to low-speed, low-rise applications such as office buildings and residential buildings up to four stories in height, low-rise department stores, malls, basement and parking garage shuttles, theater elevators, and stage lifts and freight applications of all sorts—in particular, those intended for very heavy loads. Another very useful application is for the use of disabled persons who cannot use escalators or negotiate stairs. A typical layout and dimensional data for standard plunger units are given in Fig. 32.6, along with capacities and application recommendations.

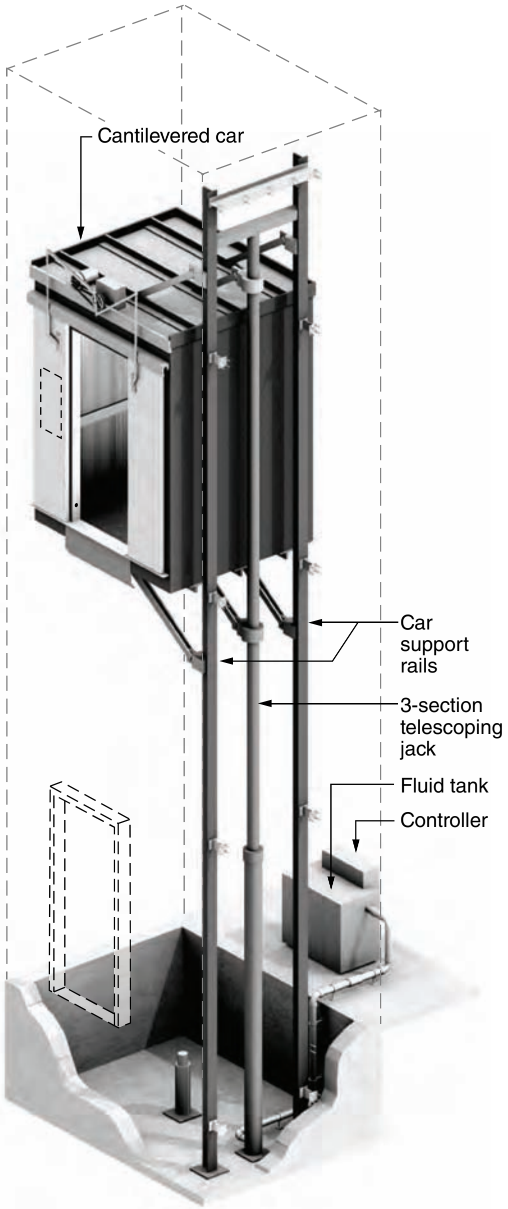


CAPACITY (LBS)	STD. SPEED (FPM)	MAXIMUM STANDARD OPENINGS	MAXIMUM STANDARD TRAVEL (i)	CLEAR OPENING (ii)	PLATFORM SIZE A WIDTH	PLATFORM SIZE B DEPTH	MINIMUM CLEAR CAB INSIDE CA WIDTH	MINIMUM CLEAR CAB INSIDE CB DEPTH	HOISTWAY C CLEAR WIDTH	HOISTWAY D(iv) WALL TO WALL	R	S	E	Q
2000	100	8	70′-0″	3′-0″	6′0″	5′-1″	5′-8″	4′-3″	7′-4″	5′-9″	3′-5″	11″	2′-1″	8″
	125		77′-0″											
2500	100	8	70′-0″	3′-6″	7′0″	5′-1″	6′-8″	4′-3″	8′-4″	5′-9″	3′-11″	11″	2′-1½″	8″
	125		76′-0″											
	150		76′-0″											
3000	100	8	70′-0″	3′-6″	7′0″	5′-7″	6′-8″	4′-9″	8′-4″	6′-3″	3′-11″	11″	2′-4⅛″	8″
	125		72′-0″											
	150		73′-0″											
3500	100	8	69′-0″	3′-6″	7′0″	6′-3″	6′-8″	5′-5″	8′-4″	6′-11″	3′-11″	11″	2′-8⅛″	8″
	125		69′-0″											
	150		69′-0″											
4000	100	8	66′-0″	4′-0″	8′0″	6′-3″	7′-8″	5′-5″	9′-4″	6′-11″	—	—	2′-8½″	8″
	125		66′-0″											
	150		66′-0″											

Fig. 32.6 *Typical dimensional, capacity, and layout data for a conventional plunger-type hydraulic elevator. Door systems are single-slide (SS) or center-opening (CO). The car can be used as a viewing-type unit by utilizing a glass wall at the back of the car. (Extracted with permission from published data of Schindler Elevator Corp.)*

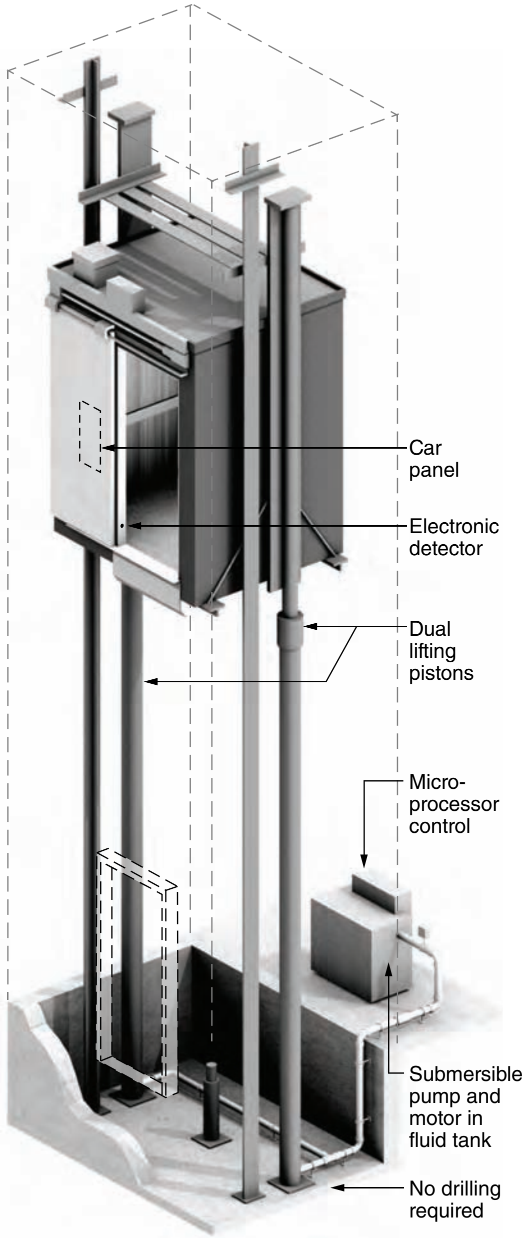
32.10 HOLE-LESS HYDRAULIC ELEVATORS

Where drilling a plunger hole presents difficulties, a hydraulic installation using a telescoping plunger or a roping arrangement can be used. The telescoping jack design, in a single-jack arrangement, is shown schematically in Fig. 32.7. As this causes a lateral stress in the building due to the cantilevered car, a dual-jack arrangement is used more frequently. When supported on both sides, as shown in Fig. 32.8, the entire vertical elevator load is transferred directly to the ground. The telescoping jack, in which



Interactive Animation

Fig. 32.7 *Hole-less hydraulic elevator driven by a single telescoping jack. The cantilevered car exerts a lateral structural load on the building. This arrangement is used less than the two-jack mechanism shown in Fig. 32.8.*



Interactive Animation

Fig. 32.8 *Dual-jack hole-less hydraulic elevator. The balanced vertical load is borne by the ground only, with no building component. The unit illustrated is suitable only for a low-rise (two-stop) installation, with a car weighing no more than 2500 lb (1134 kg).*

all sections move simultaneously, is more complex than a simple plunger unit and requires more maintenance, although maintenance is simplified by the fact that the entire length of the jack is readily accessible. The ride with the telescoping jack arrangement is not as smooth as that on a straight plunger elevator because the simultaneous movement of the jack's telescoping sections causes a degree of jerk.

32.11 ROPED HYDRAULIC ELEVATORS

The roped hydraulic arrangement is simpler than the telescoping plunger unit because it uses only a single moving jack section, compared to two or even three in a telescoping unit for the same rise. It accomplishes this by using 2:1 roping, which means that the car travels twice as far as the piston. This is accomplished by passing the rope over a pulley in the piston crosshead. One end of the rope is attached to a fixed point in the pit below the car, and the other end is attached to the base of the car (Fig. 32.9). The piston (plunger, jack) lifts the crosshead, which in turn lifts the car twice as far.

The arrangement shown in Fig. 32.9 uses a single jack and a cantilevered car. Other arrangements use two jacks to eliminate the lateral building load (Fig. 32.10). A 2:1 roping is standard in

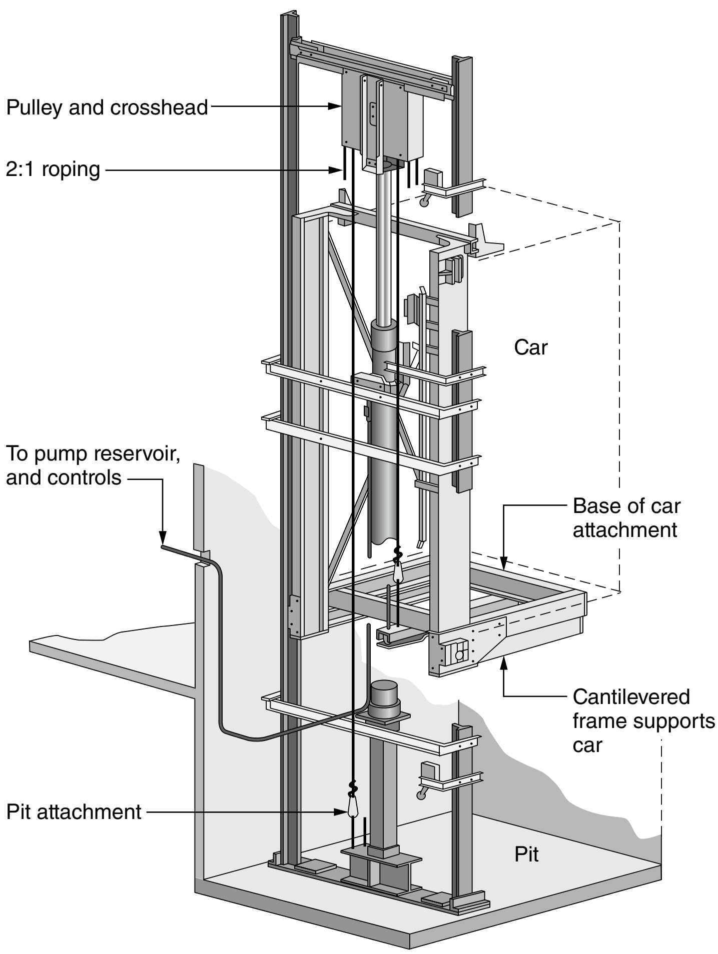


Fig. 32.9 *Low-rise residential-type elevator of the roped hydraulic type. The cantilevered car is lifted by cables from the cable crosshead, which is in turn lifted (and lowered) by the single-section telescoping piston (jack). The 2:1 roping arrangement lifts the car twice as far as the piston travels. The power unit, which includes the oil tank, pumps, and control, is usually mounted at the lower level. Control is automatic, including automatic leveling. Depending upon the specific design, the car is a 700–750-lb (318–340-kg), 30–36-fpm (0.15–0.18-m/s) unit, normally with a single-story rise. The shaftway is 16 to 26 ft*^{2} *(1.5 to 2.4 m*^{2}*), with the larger size used for a car intended to accommodate a wheelchair.*

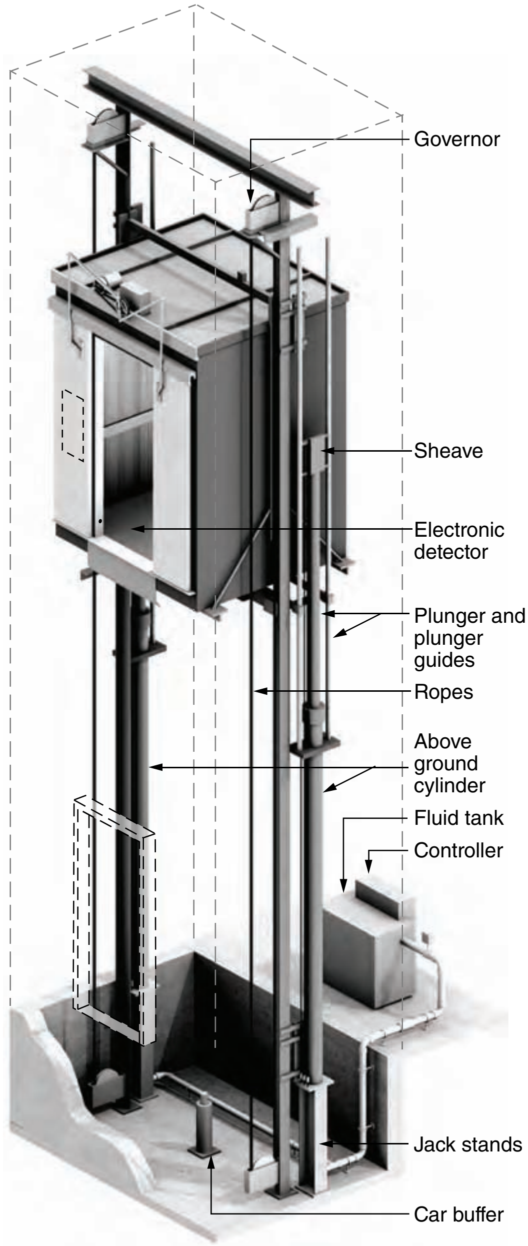


Fig. 32.10 *For heavier loads than can be readily handled by the cantilevered car in a single-jack design (Fig. 32.9), a balanced dual jack (cylinder) is used, as seen in this phantom view. This design, which can accomplish somewhat higher rise than a single-jack design, in addition to carrying much heavier loads, also requires a larger shaftway to accommodate the second cylinder and rails. A second pulley and crosshead are omitted for clarity in the drawing.*

the United States. The simplicity and reliability of the single- or double-jack roped arrangement have made it by far the most common choice for low-rise, light- to medium-duty hydraulic elevators. Because it is a roped unit, it is equipped with a slack-rope safety in addition to the other safeties used on direct-connected hydraulic systems.

PASSENGER INTERACTION ISSUES

32.12 ELEVATOR DOORS

The choice of a car and hoistway door affects the speed and quality of elevator service considerably. Doors for passenger elevators are power-operated and are synchronized with the leveling controls so that the doors are fully opened by the time a car comes to a complete stop at a landing. The closing time, however, varies with the type of door and the size of the opening. For safety reasons, the kinetic energy of an automatic door is limited to 7 ft-lb (9.5 N m) and its closing pressure to 30 lb (13.6 kg). To provide the fastest closing within this energy limitation, a center-opening door is used. Also, to reduce passenger transfer time and avoid discomfort, a clear opening of 42 in. (1.07 m) is used in most commercial installations, which permits simultaneous loading and unloading without undue passenger contact. (Some consultants feel that simultaneous passenger transfer is practical only with a 48-in. [1.2-m] clear opening; Fig. 32.11.) When an opening narrower than 36 in. (915 mm) is used, loading is delayed until unloading is complete, and the speed and quality of service are thereby markedly reduced. Such small doors are applicable only in residential or small, light-traffic buildings. Available door types are shown in Fig. 32.12.

A two-speed door design is used where space conditions dictate or where a wide opening is required. The term *two-speed* reflects the fact that the two halves of the door must travel at different speeds to complete their travel simultaneously (see Fig. 32.12*c*).

Installations can be equipped with an electronic sensing device that detects passengers in a

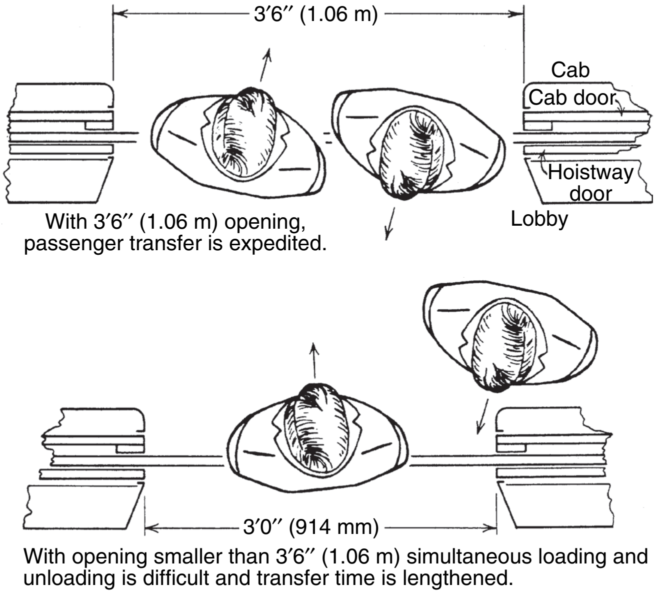


Fig. 32.11 *Transfer of passengers with door openings of different widths. With openings smaller than 3 ft, 6 in. (1.07 m), simultaneous loading and unloading is difficult and transfer time is lengthened. With a 42-in. (1.07-m) opening, large people or people with bulky outerwear may brush against each other in passing. For complete isolation of passengers, a 48-in. (1.22-m) opening may be necessary.*

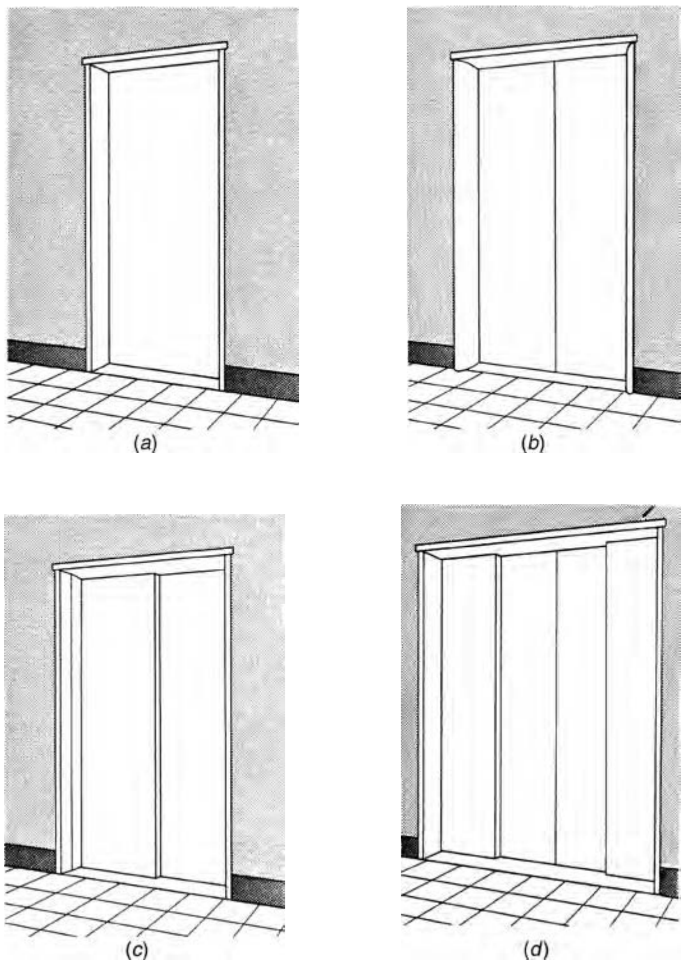


Fig. 32.12 *Typical hoistway doors and applications. (a) Single-slide door, 24 to 36 in. (610–914 mm) wide, for small commercial building or residential use. (b) Standard commercial 42-in. (1.07-m) center-opening door for office building use or 48–60-in. (1.22–1.52-m) center-opening door for hospital or service car. (c) Two-speed, 42-in. (1.07-m) general commercial use door. (d) Two-speed, center-opening, 60-in. (1.52-m) department store door for freight, passenger, and nonautomatic service.*

wide area on the landing in front of the car door rather than only directly in the door's path. Such detection, often accompanied by an audible signal, causes the car door to remain open for a predetermined length of time, or causes a closing door to reverse. These devices are particularly useful in installations where passengers cannot approach the entrance or cannot enter the car quickly—for example, riders with baggage or holding children, people in wheelchairs, and employees moving bulky objects such as beds or carts in hospitals or wheeled objects in office and industrial facilities.

All automatic elevators, regardless of whether or not equipped with detection beams, are required by ANSI to have a safety edge device on the car doors that causes the car and hoistway doors, which operate in synchrony, to reopen when the safety edge meets any obstruction. Some cars doors are arranged to "nudge" when almost closed and/or after a specific time period. ADA requirements for elevators are discussed in Section 32.14.

32.13 CARS AND SIGNALS

The primary area where the architect has a generally free hand in choosing equipment relates to the decor of the cars and the selection of hallway and car signals. A typical elevator specification is functional and describes the intended operation of the equipment, while usually including an amount to cover decor of the cars. The type and functions of signal equipment are also specified, but finish and styling are optional. Car interiors may be finished in wood paneling, plastic (Micarta or Formica), stainless steel, or almost any material desired. Floors may be tile, wood, or carpeting, as selected. Illumination may be from ceiling fixtures, coves, or a completely illuminated luminous ceiling of standard or special design. For each bank of elevators, it is wise to furnish at least one set of wall mats to protect wall finishes when cars are being used to move furniture. This is especially important where no separate service car has been provided.

Car and hallway signals and lanterns should be designed to fulfill their basic functions, consider the needs of the disabled, and coordinate with the decor of the cars and corridors. (For a discussion of the car control panel, see Section 32.27.) The call buttons should indicate the desired direction of travel, and by visual means confirm that a call has been placed. The hall lantern located at each car entrance must visually indicate the direction of travel of an arriving elevator and preferably its present location (Fig. 32.13). An audible signal should announce a car's imminent arrival. This feature allows waiting passengers to move toward the arriving car, which speeds service when there are multiple elevators in a bank. Hall stations can be equipped with special switches for fire, priority, and limited-access service, as required.

Within the car, travel direction and present location can be indicated either with separate fixtures or by indicators built into the car panel. Most manufacturers can provide voice synthesizers built into the car panel that announce the floor, direction of travel, and any other desired message such as safety or emergency messages.

32.14 REQUIREMENTS FOR THE DISABLED

Elevator manufacturers follow ADA (the Americans with Disabilities Act) requirements as a minimum, and may add additional conveniences for the disabled, to meet specific building design intent or local codes. No planning should begin until the project architect has assembled and reviewed all applicable codes and standards. Information regarding elevator accessibility requirements (which reference ASME A17.1, *Safety Code for Elevators and Escalators*) may be found on the United States Access Board's website (http://www.access-board.gov/).

The primary physical limitations addressed by the ADA are those of ambulation, sight, and hearing. Thus, to ease access for passengers in wheelchairs (or with walking aids), the ADA requires excellent car leveling, 36-in. (915-mm) minimum clear door opening (42 in. [1.1 m] recommended), delayed door closing, detection beams that reopen the door *without contact* on sensing a passenger in the door opening, inside car dimensions that permit turning a wheelchair, buttons and emergency controls within easy reach, and appropriate car furnishings.

For those with sight impairment, the ADA requires audible signals in addition to easily seen

(a) (b) (c)

Fig. 32.13 *(a) Typical single-slide-door elevator with call buttons and travel direction indicators. (b) LED arrowheads to indicate the direction of the elevator car travel. (c) Elevator pushbuttons to call the elevator. (Courtesy of Karen Tse.)*

and recognized visual ones, both in the car and at landings, to indicate call registration, car approach, car landing, direction of travel, floor, car position, and so on. In this connection, a voice synthesizer is of invaluable assistance. In addition, Braille plates adjacent to car floor buttons, and large, easily recognizable symbols adjacent to passenger-controlled emergency controls are to be used. Hearing-impaired passengers are assisted by the large visual signals required for sight-impaired passengers. In addition, call buttons must visually indicate that a call has been placed and likewise indicate when the call has been answered. Many of these ideas also make life easier for all passengers. A note of caution: Delayed door closing may increase overall travel time appreciably. In buildings with substantial traffic peaks, this factor needs to be considered when designing the elevator system.

Requirements of the ADA that apply to elevators are presented in Fig. 32.14, with accompanying illustrations (figure and chapter numbers within the illustration are ADA references).

ELEVATOR CAR CONTROL

32.15 DRIVE CONTROL

The movement of an elevator car and all of its parts is controlled by three different systems that combine and interact to provide a unified control system. The *supervisory system* controls a bank of elevators as a group and dictates which car answers which call. The *operational control* system determines when and where physical motion of a car and its doors should occur. This system deals with the operation of the car doors and the integration of car buttons, lanterns, and passenger-operated devices into the overall control and indicating system. The operating control system passes information about car and door control to the *motion control* system (also known as *drive control*). Motion control determines the car's acceleration, velocity, braking, leveling, and regenerative braking, plus all aspects of door motion.

Elevator *car* control is separate and distinct from the control system that governs the functioning of a group of cars acting as a system. That arrangement is generally designated the *supervisory system* and is discussed separately.

Elevator car acceleration and deceleration are accomplished by controlling the speed of the motor that drives the elevator traction machine. This speed control can be accomplished in a number of ways, all of which are in use in elevator installations. They are:

- Thyristor control of an asynchronous (squirrel cage) AC traction motor
- Thyristor control of a DC traction motor
- Motor-generator (m-g) set control of a DC traction motor (Ward–Leonard system)
- Variable-voltage, variable-frequency (VVVF) control of an asynchronous AC traction motor

Rheostatic control of single and multispeed AC motors is essentially obsolete and therefore is not discussed. Each system is described briefly in the following sections, and applicability, advantages, and disadvantages are noted.

32.16 THYRISTOR CONTROL, AC AND DC

(a) AC

High-power transistors make accurate speed control of inexpensive AC squirrel-cage motors practical by the simple expedient of supplying carefully regulated variable voltage to the motor. The resultant speed control is smooth and stepless, making it applicable to passenger elevator installations. However, the high motor slip caused by the constant frequency of the variable-voltage AC supply causes large thermal losses with resultant low operating efficiency. In addition, the "chopper," which is used to provide the necessary voltage control, introduces undesirable harmonics into the power system in considerable quantity. These harmonics cause undesirable radio noise and can cause system component overheating. Finally, the system's low power factor increases line losses and necessitates increased feeder sizes. As a result, this option, which is applicable to low- and mid-rise passenger service (maximum rise 250 ft [76 m] and maximum car speed of 350 fpm [1.8 m/s]), using geared machines, has been largely replaced by VVVF control (see Section 32.18).

(b) DC

Excellent ride quality can be had by utilizing the DC version of thyristor control (see Fig. 32.15*a*) to supply variable voltage to a DC traction motor. This arrangement provides the high-quality ride and leveling characteristic of DC drives and removes the rise and speed limitations of its AC counterpart, but

407 Elevators

407.1 General. Elevators shall comply with 407 and with ASME A17.1 (incorporated by reference, see "Referenced Standards" in Chapter 1). They shall be passenger elevators as classified by ASME A17.1. Elevator operation shall be automatic.

> **Advisory 407.1 General.** The ADA and other Federal civil rights laws require that accessible features be maintained in working order so that they are accessible to and usable by those people they are intended to benefit. Building owners should note that the ASME Safety Code for Elevators and Escalators requires routine maintenance and inspections. Isolated or temporary interruptions in service due to maintenance or repairs may be unavoidable; however, failure to take prompt action to effect repairs could constitute a violation of Federal laws and these requirements.

Fig. 32.14 *ADA requirements for elevators. (Reprinted from 2010 ADA Standards, U.S. Department of Justice.)*

407.2 Elevator Landing Requirements. Elevator landings shall comply with 407.2.

407.2.1 Call Controls. Where elevator call buttons or keypads are provided, they shall comply with 407.2.1 and 309.4. Call buttons shall be raised or flush.

EXCEPTION: Existing elevators shall be permitted to have recessed call buttons.

407.2.1.1 Height. Call buttons and keypads shall be located within one of the reach ranges specified in 308, measured to the centerline of the highest *operable part*.

EXCEPTION: Existing call buttons and existing keypads shall be permitted to be located at 54 inches (1370 mm) maximum above the finish floor, measured to the centerline of the highest *operable part*.

407.2.1.2 Size. Call buttons shall be ¾ inch (19 mm) minimum in the smallest dimension.

EXCEPTION: Existing elevator call buttons shall not be required to comply with 407.2.1.2.

407.2.1.3 Clear Floor or Ground Space. A clear floor or ground *space* complying with 305 shall be provided at call controls.

Advisory 407.2.1.3 Clear Floor or Ground Space. The clear floor or ground space required at elevator call buttons must remain free of obstructions including ashtrays, plants, and other decorative elements that prevent wheelchair users and others from reaching the call buttons. The height of the clear floor or ground space is considered to be a volume from the floor to 80 inches (2030 mm) above the floor. Recessed ashtrays should not be placed near elevator call buttons so that persons who are blind or visually impaired do not inadvertently contact them or their contents as they reach for the call buttons.

407.2.1.4 Location. The call button that designates the up direction shall be located above the call button that designates the down direction.

EXCEPTION: Destination-oriented elevators shall not be required to comply with 407.2.1.4.

Advisory 407.2.1.4 Location Exception. A destination-oriented elevator system provides lobby controls enabling passengers to select floor stops, lobby indicators designating which elevator to use, and a car indicator designating the floors at which the car will stop. Responding cars are programmed for maximum efficiency by reducing the number of stops any passenger experiences.

407.2.1.5 Signals. Call buttons shall have visible signals to indicate when each call is registered and when each call is answered.

EXCEPTIONS: **1.** Destination-oriented elevators shall not be required to comply with 407.2.1.5 provided that visible and audible signals complying with 407.2.2 indicating which elevator car to enter are provided.

2. Existing elevators shall not be required to comply with 407.2.1.5.

407.2.1.6 Keypads. Where keypads are provided, keypads shall be in a standard telephone keypad arrangement and shall comply with 407.4.7.2.

Fig. 32.14 *(Continued)*

407.2.2 Hall Signals. Hall signals, including in-car signals, shall comply with 407.2.2.

407.2.2.1 Visible and Audible Signals. A visible and audible signal shall be provided at each hoistway entrance to indicate which car is answering a call and the car's direction of travel. Where in-car signals are provided, they shall be visible from the floor area adjacent to the hall call buttons.

EXCEPTIONS: 1. Visible and audible signals shall not be required at each destination-oriented elevator where a visible and audible signal complying with 407.2.2 is provided indicating the elevator car designation information.

2. In existing elevators, a signal indicating the direction of car travel shall not be required.

407.2.2.2 Visible Signals. Visible signal fixtures shall be centered at 72 inches (1830 mm) minimum above the finish floor or ground. The visible signal *elements* shall be 2-½ inches (64 mm) minimum measured along the vertical centerline of the *element*. Signals shall be visible from the floor area adjacent to the hall call button.

EXCEPTIONS: 1. Destination-oriented elevators shall be permitted to have signals visible from the floor area adjacent to the hoistway entrance.

2. Existing elevators shall not be required to comply with 407.2.2.2.

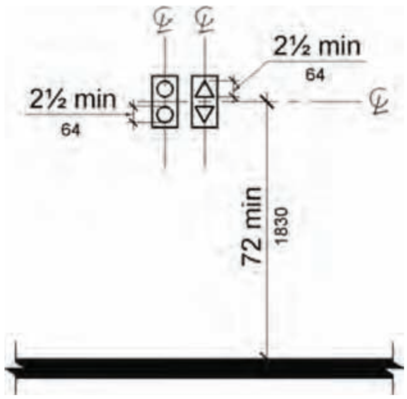


Figure 407.2.2.2
Visible Hall Signals

407.2.2.3 Audible Signals. Audible signals shall sound once for the up direction and twice for the down direction, or shall have verbal annunciators that indicate the direction of elevator car travel. Audible signals shall have a frequency of 1500 Hz maximum. Verbal annunciators shall have a frequency of 300 Hz minimum and 3000 Hz maximum. The audible signal and verbal annunciator shall be 10 dB minimum above ambient, but shall not exceed 80 dB, measured at the hall call button.

EXCEPTIONS: 1. Destination-oriented elevators shall not be required to comply with 407.2.2.3 provided that the audible tone and verbal announcement is the same as those given at the call button or call button keypad.

2. Existing elevators shall not be required to comply with the requirements for frequency and dB range of audible signals.

Fig. 32.14 *(Continued)*

407.2.2.4 Differentiation. Each destination-oriented elevator in a bank of elevators shall have audible and visible means for differentiation.

407.2.3 Hoistway Signs. Signs at elevator hoistways shall comply with 407.2.3.

407.2.3.1 Floor Designation. Floor designations complying with 703.2 and 703.4.1 shall be provided on both jambs of elevator hoistway entrances. Floor designations shall be provided in both *tactile characters* and braille. *Tactile characters* shall be 2 inches (51 mm) high minimum. A *tactile* star shall be provided on both jambs at the main entry level.

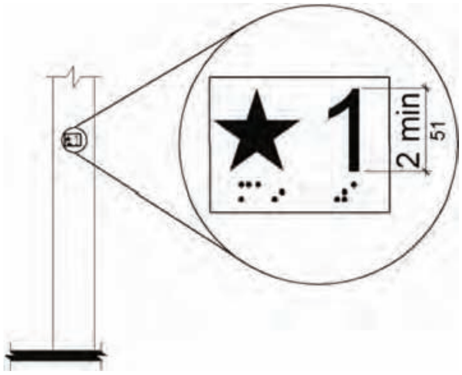


Figure 407.2.3.1
Floor Designations on Jambs of Elevator Hoistway Entrances

407.2.3.2 Car Designations. Destination-oriented elevators shall provide *tactile* car identification complying with 703.2 on both jambs of the hoistway immediately below the floor designation. Car designations shall be provided in both *tactile characters* and braille. *Tactile characters* shall be 2 inches (51 mm) high minimum.

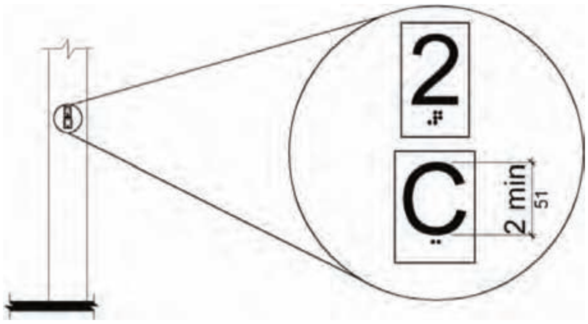


Figure 407.2.3.2
Car Designations on Jambs of Destination-Oriented Elevator Hoistway Entrances

Fig. 32.14 *(Continued)*

407.3 Elevator Door Requirements. Hoistway and car doors shall comply with 407.3.

407.3.1 Type. Elevator doors shall be the horizontal sliding type. Car gates shall be prohibited.

407.3.2 Operation. Elevator hoistway and car doors shall open and close automatically.
EXCEPTION: Existing manually operated hoistway swing doors shall be permitted provided that they comply with 404.2.3 and 404.2.9. Car door closing shall not be initiated until the hoistway door is closed.

407.3.3 Reopening Device. Elevator doors shall be provided with a reopening device complying with 407.3.3 that shall stop and reopen a car door and hoistway door automatically if the door becomes obstructed by an object or person.
EXCEPTION: Existing elevators with manually operated doors shall not be required to comply with 407.3.3.

407.3.3.1 Height. The device shall be activated by sensing an obstruction passing through the opening at 5 inches (125 mm) nominal and 29 inches (735 mm) nominal above the finish floor.

407.3.3.2 Contact. The device shall not require physical contact to be activated, although contact is permitted to occur before the door reverses.

407.3.3.3 Duration. Door reopening devices shall remain effective for 20 seconds minimum.

407.3.4 Door and Signal Timing. The minimum acceptable time from notification that a car is answering a call or notification of the car assigned at the means for the entry of destination information until the doors of that car start to close shall be calculated from the following equation:

T = D/(1.5 ft/s) or T = D/(455 mm/s) = 5 seconds minimum where T equals the total time in seconds and D equals the distance (in feet or millimeters) from the point in the lobby or corridor 60 inches (1525 mm) directly in front of the farthest call button controlling that car to the centerline of its hoistway door.
EXCEPTIONS: 1. For cars with in-car lanterns, T shall be permitted to begin when the signal is visible from the point 60 inches (1525 mm) directly in front of the farthest hall call button and the audible signal is sounded.
2. Destination-oriented el evators shall not be required to comply with 407.3.4.

407.3.5 Door Delay. Elevator doors shall remain fully open in response to a car call for 3 seconds minimum.

407.3.6 Width. The width of elevator doors shall comply with Table 407.4.1.
EXCEPTION: In existing elevators, a power-operated car door complying with 404.2.3 shall be permitted.

407.4 Elevator Car Requirements. Elevator cars shall comply with 407.4.

407.4.1 Car Dimensions. Inside dimensions of elevator cars and clear width of elevator doors shall comply with Table 407.4.1.

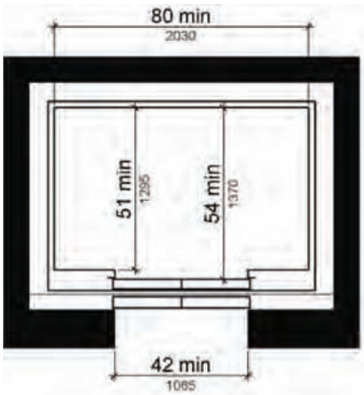
Fig. 32.14 *(Continued)*

EXCEPTION: Existing elevator car configurations that provide a clear floor area of 16 square feet (1.5 m^2) minimum and also provide an inside clear depth 54 inches (1370 mm) minimum and a clear width 36 inches (915 mm) minimum shall be permitted.

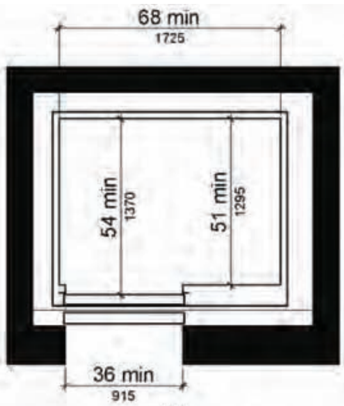
Table 407.4.1 Elevator Car Dimensions

	Minimum Dimensions			
Door Location	**Door Clear Width**	**Inside Car, Side to Side**	**Inside Car, Back Wall to Front Return**	**Inside Car, Back Wall to Inside Face of Door**
Centered	42 inches (1065 mm)	80 inches (2030 mm)	51 inches (1295 mm)	54 inches (1370 mm)
Side (off-centered)	36 inches (915 mm)[1]	68 inches (1725 mm)	51 inches (1295 mm)	54 inches (1370 mm)
Any	36 inches (915 mm)[1]	54 inches (1370 mm)	80 inches (2030 mm)	80 inches (2030 mm)
Any	36 inches (915 mm)[1]	60 inches (1525 mm)[2]	60 inches (1525 mm)[2]	60 inches (1525 mm)[2]

1. A tolerance of minus 5/8 inch (16 mm) is permitted.
2. Other car configurations that provide a turning *space* complying with 304 with the door closed shall be permited.



(a)
centered door



(b)
side (off-centered) door

Figure 407.4.1
Elevator Car Dimensions

Fig. 32.14 *(Continued)*

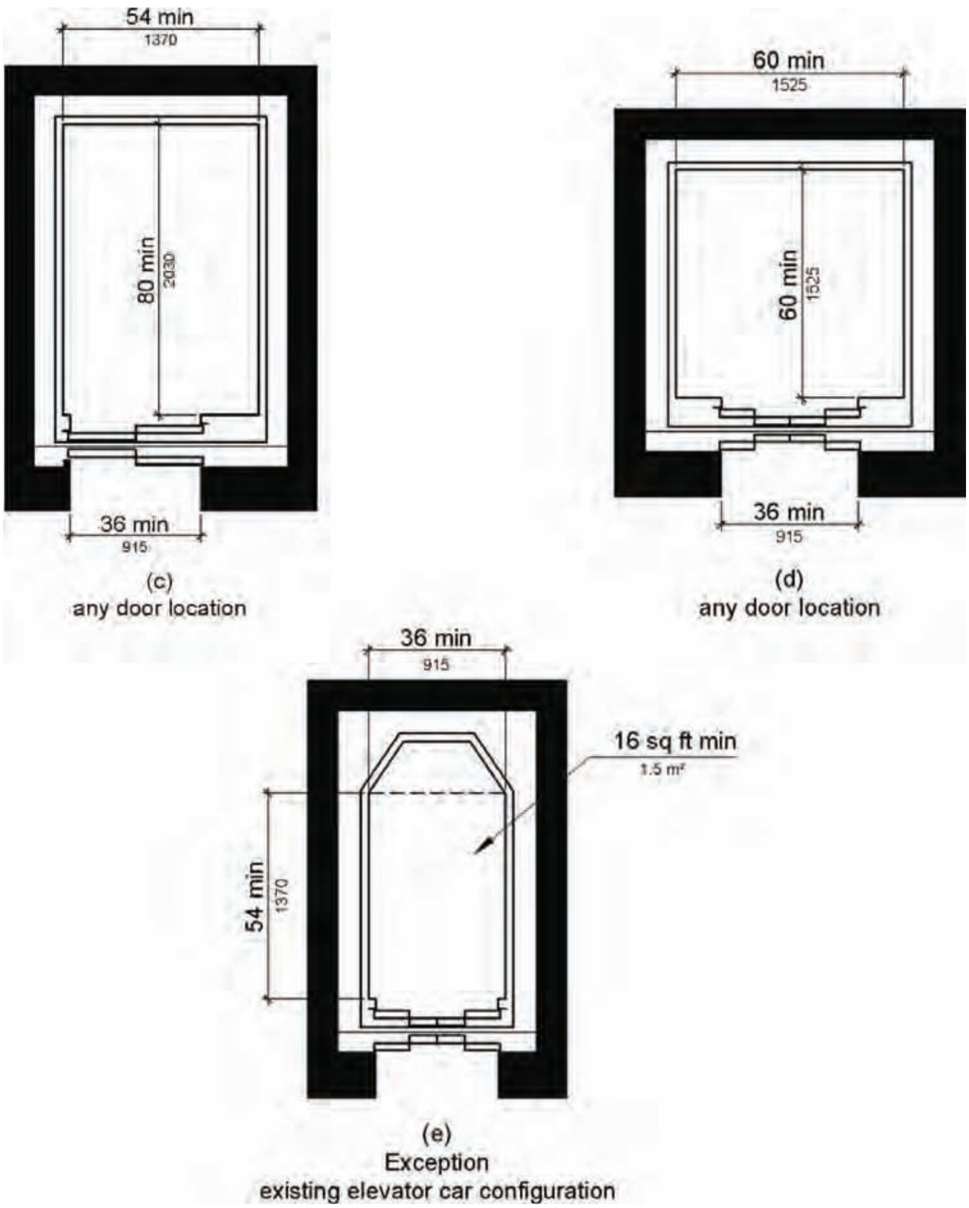


Figure 407.4.1
Elevator Car Dimensions

Fig. 32.14 *(Continued)*

407.4.2 Floor Surfaces. Floor surfaces in elevator cars shall comply with 302 and 303.

407.4.3 Platform to Hoistway Clearance. The clearance between the car platform sill and the edge of any hoistway landing shall be 1¼ inch (32 mm) maximum.

407.4.4 Leveling. Each car shall be equipped with a self-leveling feature that will automatically bring and maintain the car at floor landings within a tolerance of ½ inch (13 mm) under rated loading to zero loading conditions.

407.4.5 Illumination. The level of illumination at the car controls, platform, car threshold and car landing sill shall be 5 foot candles (54 lux) minimum.

407.4.6 Elevator Car Controls. Where provided, elevator car controls shall comply with 407.4.6 and 309.4.

EXCEPTION: In existing elevators, where a new car operating panel complying with 407.4.6 is provided, existing car operating panels shall not be required to comply with 407.4.6.

407.4.6.1 Location. Controls shall be located within one of the reach ranges specified in 308.

EXCEPTIONS: 1. Where the elevator panel serves more than 16 openings and a parallel approach is provided, buttons with floor designations shall be permitted to be 54 inches (1370 mm) maximum above the finish floor.

2. In existing elevators, car control buttons with floor designations shall be permitted to be located 54 inches (1370 mm) maximum above the finish floor where a parallel approach is provided.

407.4.6.2 Buttons. Car control buttons with floor designations shall comply with 407.4.6.2 and shall be raised or flush.

EXCEPTION: In existing elevators, buttons shall be permitted to be recessed.

407.4.6.2.1 Size. Buttons shall be 3/4 inch (19 mm) minimum in their smallest dimension.

407.4.6.2.2 Arrangement. Buttons shall be arranged with numbers in ascending order. When two or more columns of buttons are provided they shall read from left to right.

407.4.6.3 Keypads. Car control keypads shall be in a standard telephone keypad arrangement and shall comply with 407.4.7.2.

407.4.6.4 Emergency Controls. Emergency controls shall comply with 407.4.6.4.

407.4.6.4.1 Height. Emergency control buttons shall have their centerlines 35 inches (890 mm) minimum above the finish floor.

407.4.6.4.2 Location. Emergency controls, including the emergency alarm, shall be grouped at the bottom of the panel.

407.4.7 Designations and Indicators of Car Controls. Designations and indicators of car controls shall comply with 407.4.7.

Fig. 32.14 *(Continued)*

EXCEPTION: In existing elevators, where a new car operating panel complying with 407.4.7 is provided, existing car operating panels shall not be required to comply with 407.4.7.

407.4.7.1 Buttons. Car control buttons shall comply with 407.4.7.1.

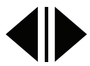
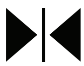
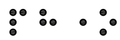
407.4.7.1.1 Type. Control buttons shall be identified by *tactile characters* complying with 703.2.

407.4.7.1.2 Location. Raised *character* and braille designations shall be placed immediately to the left of the control button to which the designations apply.

EXCEPTION: Where *space* on an existing car operating panel precludes *tactile* markings to the left of the controls, markings shall be placed as near to the control as possible.

407.4.7.1.3 Symbols. The control button for the emergency stop, alarm, door open, door close, main entry floor, and phone, shall be identified with *tactile* symbols as shown in Table 407.4.7.1.3.

Table 407.4.7.1.3 Elevator Control Button Identification

Control Button	Tactile Symbol	Braille Message
Emergency Stop		 “ST”OP Three cells
Alarm		 AL“AR”M Four cells
Door Open		 OP“EN” Three cells
Door Close		 CLOSE Five cells
Main Entry Floor		 MA“IN” Three cells
Phone		 PH“ONE” Four cells

407.4.7.1.4 Visible Indicators. Buttons with floor designations shall be provided with visible indicators to show that a call has been registered. The visible indication shall extinguish when the car arrives at the designated floor.

Fig. 32.14 *(Continued)*

407.4.7.2 Keypads. Keypads shall be identified by *characters* complying with 703.5 and shall be centered on the corresponding keypad button. The number five key shall have a single raised dot. The dot shall be 0.118 inch (3 mm) to 0.120 inch (3.05 mm) base diameter and in other aspects comply with Table 703.3.1.

407.4.8 Car Position Indicators. Audible and visible car position indicators shall be provided in elevator cars.

407.4.8.1 Visible Indicators. Visible indicators shall comply with 407.4.8.1.

407.4.8.1.1 Size. *Characters* shall be ½ inch (13 mm) high minimum.

407.4.8.1.2 Location. Indicators shall be located above the car control panel or above the door.

407.4.8.1.3 Floor Arrival. As the car passes a floor and when a car stops at a floor served by the elevator, the corresponding *character* shall illuminate.

EXCEPTION: Destination-oriented elevators shall not be required to comply with 407.4.8.1.3 provided that the visible indicators extinguish when the call has been answered.

407.4.8.1.4 Destination Indicator. In destination-oriented elevators, a display shall be provided in the car with visible indicators to show car destinations.

407.4.8.2 Audible Indicators. Audible indicators shall comply with 407.4.8.2.

407.4.8.2.1 Signal Type. The signal shall be an automatic verbal annunciator which announces the floor at which the car is about to stop.

EXCEPTION: For elevators other than destination-oriented elevators that have a rated speed of 200 feet per minute (1 m/s) or less, a non-verbal audible signal with a frequency of 1500 Hz maximum which sounds as the car passes or is about to stop at a floor served by the elevator shall be permitted.

407.4.8.2.2 Signal Level. The verbal annunciator shall be 10 dB minimum above ambient, but shall not exceed 80 dB, measured at the annunciator.

407.4.8.2.3 Frequency. The verbal annunciator shall have a frequency of 300 Hz minimum to 3000 Hz maximum.

407.4.9 Emergency Communication. Emergency two-way communication systems shall comply with 308. *Tactile* symbols and *characters* shall be provided adjacent to the device and shall comply with 703.2.

Fig. 32.14 *(Continued)*

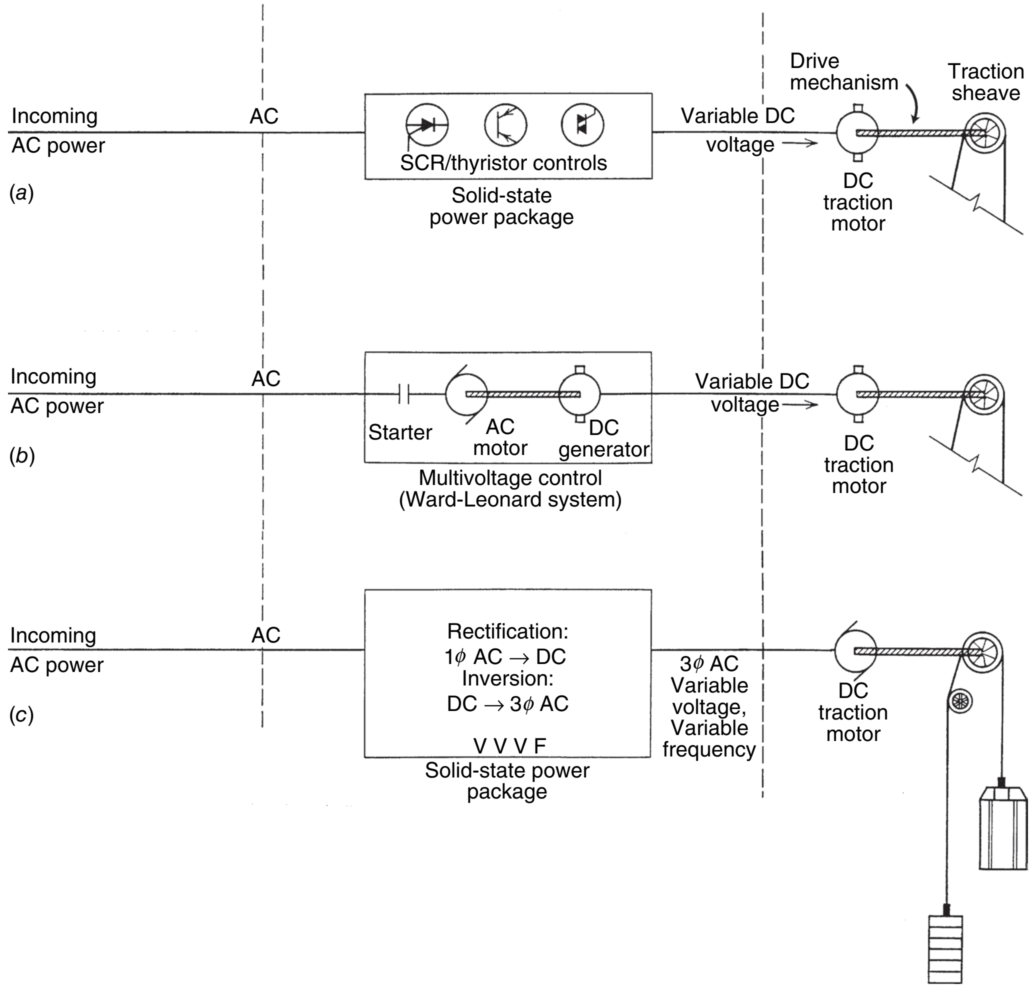


Fig. 32.15 *Arrangement of electric speed-control equipment for elevator drives. (a) Solid-state, silicon-controlled rectifier (SCR) thyristor control produces variable-voltage DC and finds application in good-quality new and retrofit medium- and high-speed installations. (b) The traditional Ward–Leonard (m-g) system, which produces finely controlled, variable-voltage DC. This is the system in use today in the vast majority of existing high-quality installations. (c) Variable-voltage, variable-frequency (VVVF) AC is energy-efficient, highly accurate, and applicable to all types of installations.*

not the system's inherent low power factor, heavy line harmonics, and high machine room thermal losses. Line harmonics can be sharply reduced by the use of power line filters. This control system is widely used today, with both geared and gearless traction machines as applicable, for installations of all rises and car speeds. Its extremely smooth ride makes it one of the three systems of choice in high-quality construction. The other two systems are the traditional Ward–Leonard variable-voltage DC system and the VVVF AC system.

32.17 VARIABLE-VOLTAGE DC MOTOR CONTROL

Before the development of electronic motor control, the only practical way of obtaining the precise motor speed control necessary for smooth, stepless elevator operation was to provide a variable DC voltage to a DC traction motor. This variable DC voltage was obtained from an auxiliary m-g set comprising an AC motor and a DC generator. This arrangement (see Fig. 32.15*b*) is known as a *Ward–Leonard system* or as a *unit multivoltage* (UMV) drive. Although this arrangement has disadvantages, it is a classic high-quality elevator drive arrangement and is found in the vast majority of better-quality geared and gearless installations built before 1990. The disadvantages of this system—low overall efficiency, expensive machines, high thermal losses in machine rooms, high maintenance costs for three rotating machines, and high noise levels—were, until the development of a practical VVVF system, accepted as the price of a system that operated faultlessly, with great accuracy at all speeds, and for long periods of time, given proper maintenance. As noted previously, it is today still one of the three principal drive control systems being used in new installations. Its primary advantage over VVVF control is that it is "forgiving" of a less than ideal building power supply.

In modernization work, buildings with existing Ward–Leonard systems are frequently converted to solid-state DC thyristor control. This change maintains the excellent ride characteristics of variable-voltage DC traction machine installations while improving system performance by replacing the auxiliary m-g set with a low-loss, low-maintenance, quiet, solid-state thyristor drive control.

32.18 VARIABLE-VOLTAGE, VARIABLE-FREQUENCY AC MOTOR CONTROL

This system (see Fig. 32.15*c*), which is entirely solid-state, is (in the opinion of many elevator professionals) the drive system of choice for all high-quality new installations of any speed or rise. The system consists of a rectifier, which changes the incoming AC to DC, and an inverter, which creates variable-voltage, infinitely variable-frequency, three-phase AC from the (rectified) DC. This AC is then applied to a standard squirrel-cage AC motor, which operates essentially at the speed corresponding to the frequency of the input. By maintaining a constant voltage-to-frequency ratio input to the traction motor, it is possible to provide continuously variable, highly accurate speed control at extremely high efficiencies throughout the full speed range of the motor. This is precisely what is required for high-quality geared and gearless installations, without the energy losses associated with the auxiliary m-g set associated with UMV control. The VVVF speed control system eliminates most of the disadvantages of the solid-state thyristor control system and has the following characteristics:

- Overall system efficiency is high at all motor speeds.
- Traction motors are economical single-speed squirrel-cage AC.
- Motors are 10% to 15% smaller than those of other drive systems.
- System power factor is close to unity.
- Line harmonics are lower than with thyristor controls.
- Speed control and leveling are equal to DC traction motor control.
- Equipment is 98% solid-state, thus requiring minimum maintenance.
- Electric energy use and peak loads are reduced, thus reducing electric billings by up to 35%.
- The system is applicable to all rises and speeds.
- Machine rooms are smaller, cooler, and quieter than those using Ward–Leonard UMV controls.

The preceding discussion can be summarized with tabular comparisons of the various drive systems in use today (Tables 32.2 and 32.3). The exact

TABLE 32.3 Comparative Characteristics of Elevator Drive Systems

Type	Rise ft (m)	Speed fpm (m/s)	Control	Initial Cost	Operating Cost	Performance
Geared AC	250 (76)	150–350 (0.8–1.8)	Thyristor	Medium	Medium	Fair
	300 (91)	150–450 (0.8-2.3)	VVVF	High	Low	Excellent
Geared DC	175 (53)	50–450 (0.3–2.3)	UMV	High	High	Excellent
	250 (76)	50–450 (0.3–2.3)	Thyristor	Medium	Low	Very good
Gearless DC	Unlimited	400–1200 (2.0–6.1)	UMV	High	High	Excellent
			Thyristor	Medium	Low	Very good
Gearless AC	Unlimited	400–2000 (2.0–10.2)	VVVF	Medium	Low	Excellent

Note: Life of equipment is generally indefinite except for the worm and gear of a geared unit, which have a 30- to 40-year life.

extent of improvement possible when changing to solid-state equipment in a retrofit job depends on the quality of both the old and new systems. It is greatest when a microcomputer group control system replaces a relay-logic terminal dispatch system.

32.19 ELEVATOR OPERATING CONTROL

Assuming an elevator system is energized and at rest, registration of a call from a lobby station or an upper-floor corridor activates the system. The particular elevator car that answers the call is selected by the supervisory system. In a UMV system, the car's m-g set is started, whereas with solid-state motion control power is available immediately. Switching devices in the car control panel release the brake, energize the elevator motor, and accelerate the car to its rated speed. Reverse operations are initiated when decelerating and stopping (landing) the car. When the car stops, the brake holds the sheave and elevator stationary.

The motion of a single car is determined by the action of three principal items of equipment: the car controller, the motion controls, and the system supervisory equipment. The action of the last equipment is discussed in Sections 32.20 to 32.24. The function of the car controller is to provide information on the car's exact location, car panel calls, and hall calls. This information is fed into the supervisory system and the motion control equipment, which in turn act to initiate all the procedures necessary to answer all calls via the individual car controller panels. The car controller panel also supplies the necessary signals to car and hall lanterns that indicate the car position and direction of travel.

32.20 SYSTEM CONTROL REQUIREMENTS

An operating system provides for the automatic response of a group of cars to calls for service. An effective system must process information regarding all hall calls and car calls, car travel directions, and car position (in relation to each other and in relation to the call requirements), plus the trends of traffic. The last is required to allow the system to anticipate demand rather than just react to it. Because traffic and calls are never static, a control system that can satisfy all these demands in a large elevator system is necessarily an extremely sophisticated one. On small systems, the operating control is much simpler, as described in later sections. Throughout the discussion that follows, solid-state systems are assumed.

32.21 SINGLE AUTOMATIC PUSHBUTTON CONTROL

This system is the simplest of the passenger-operated automatic control schemes. It handles only one call at a time, providing an uninterrupted trip for each call. A single corridor button at each level can register a call only when the car is not in motion. This system is used only in private residences and for light-use freight elevators.

32.22 COLLECTIVE CONTROL

Cars stop at each floor registering a call irrespective of direction, hence the term *collective*. This leads to slow and annoying service. As a result, this system is no longer used in new installations in the United States, although it is common in other countries.

32.23 SELECTIVE COLLECTIVE OPERATION

This type of collective operation is "selective" in that it is arranged to collect all waiting "up" calls on the trip up and all "down" calls on the trip down. The control system stores all calls until they are answered, and automatically reverses the direction of travel at the highest and lowest calls. When all calls have been cleared, the car will remain at the floor of its last stop awaiting the next call. Any hall button call will set the car in operation.

Selective collective control is standard in locations where service requirements are moderate, such as in apartment houses, small offices, and professional buildings. Because these locations often require more than one car, a group control scheme for up to three cars automatically assigns each hall call to the car best situated to answer it, prevents more than one car from answering a call, allows one car to be detached for freight duty, and automatically parks cars at the ground floor when they are not required.

Although selective collective control is in common use for residential and other buildings with light- to moderate-service requirements, its inherent and strong tendency toward bunching of cars can result in long waiting periods. This characteristic is particularly annoying with groups of three cars. Frequently, a passenger arrives at a landing to find that all three cars have just passed, going in the same direction. The result is that service is only slightly better than what would be rendered by a single car, except that the load (handling) capacity is greater. For this reason, operation of more than two cars with this system is not recommended, and operation of more than three cars is not feasible.

32.24 COMPUTERIZED SYSTEM CONTROL

Prior to the advent of computer supervisory control, large banks of elevators were controlled by lobby-based human "starters" who attempted, with limited success, to recognize and anticipate traffic patterns and thus speed service. Due to the huge amount of information that had to be processed, service was frequently less than satisfactory—particularly during heavy traffic. This situation changed with the advent of computerized, microprocessor-controlled operating systems.

A satisfactory control system must continuously monitor demand, and control each car's motion in response to demand only; that is, it must analyze all the possibilities and answer each call in optimum fashion. The definition of *optimum* depends, of course, on the system design strategy, and this varies among manufacturers. Such a system is possible only with the aid of a central computer combined with programmable microprocessor-controlled peripherals, because the amount of data that must be collected and instantaneously processed is enormous.

All manufacturers attempt to optimize the parameters by which system quality is measured—specifically, to minimize interval, hall waiting time, and average trip time. How this is accomplished depends on the relative weight assigned to each item of input data in an extremely complex computer algorithm. One manufacturer uses an algorithm that calculates a figure of merit for *each* car to answer *each* waiting hall call. The number arrived at represents the weighted sum of the projected passenger hall waiting time (interval and hall wait time) and traveling passenger delay (average trip time). The car with the best figure of merit (minimum time) is assigned to the landing call. Another manufacturer uses a somewhat simpler dynamic call allocation algorithm that relies on the high-speed calculation capabilities of a central computer to make a last-moment decision as to which car answers which call. Another algorithm, in addition to analyzing each car's capability to answer a call, calculates the effect of any decision on the overall elevator service quality for the building and uses this factor as well in the final decision.

Still another algorithm uses a car dispatch program based on preprogrammed and learned traffic patterns, modified by the history of the previous few minutes of operation. In the basic program, each car computes its own response time to a waiting hall call—considering its own position, velocity, and car calls—and compares it to that of all other cars in the group. The car that will provide optimum hall call service time (waiting time plus trip time) answers the hall call. To facilitate this type of car "bidding" for calls, some systems are arranged so that each car controller can act as a master group controller. At any one time, one car in the group acts as the master, but if it is taken out of service, another car controller becomes the master.

In addition, some programs use an artificial intelligence module to learn traffic data and history and continuously change the car-dispatching mode. These changes consist in part of sectoring or zoning the building so that cars are grouped to provide optimal service. This type of system is particularly useful in buildings with single-floor- or multifloor-use occupants with repetitive traffic patterns. Most algorithms permit overriding the program mode in response to crowd sensors or to particularly heavy, concentrated service demand, such as might occur if the occupants of an entire floor left the building at an unusual hour.

The actual program logic for even a small group supervisory traffic control system is beyond the scope of this book, but its guidelines are not. An adequate system should:

- Be programmed initially for the anticipated service needs. These needs can be analyzed in existing buildings with computerized traffic analyzers (Fig. 32.16).
- Be reprogrammable to meet changes in building needs at nominal cost and with minimum shutdown time. It must be possible to detach cars from the system during testing, reprogramming, and routine maintenance, and to provide minimal service even during off-hours.
- Provide for priority calls (based on landing waiting times), statistical analysis of traffic in order to anticipate patterns, adaptive (zoned) car parking to meet specific needs, adjustable door timing based on the type of call (lobby, landing, car), backup dispatch means (in case of dispatch system failure), and automatic call cutout for constant (stuck) signals.
- Provide means for viewing elevator traffic information from selected locations (lobby or management office) and for obtaining a hard copy of this information—both as stored and real-time data. This information-handling equipment must provide a fault mode that stores, displays, and diagnoses system operating faults. The owner/manager unit may have on-site control and reprogramming capabilities if so required.
- Provide additional functions such as emergency power elevator selection and control (see Section 32.45), priority service, selective hall/car call cutout, swing (separate) car operation, and hoistway access controls for maintenance.
- Provide, where specifically required by the building management, a riot-control feature (allowing access limits at entrance levels), crossover floor operation in a zoned system, convention service (intense short-time usage at selected levels), and controlled access at given floors and for specific occupants.
- Be fully coordinated with the fire protection system in accordance with the local fire regulations (see Section 32.46).
- Act in consonance with the elevator security equipment so that operation of security/alarm devices initiates automatic elevator motion control procedures. This too must be coordinated with the local security authorities, and the automatic procedures must be subject to manual override (see Section 32.47).

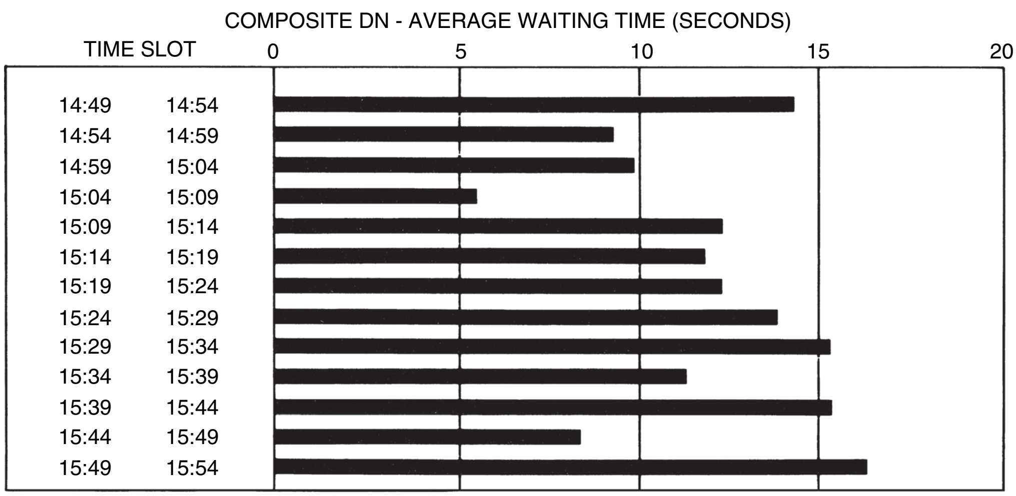


Fig. 32.16 *Building elevator traffic studies can be performed quickly and accurately using a software-based traffic analyzer with multiple inputs. Accumulated data on call registration, response time, waiting time, maximum interval, cars in service, and so on, can be presented graphically. (Courtesy of UNITEC Parts Co.)*

Proper operation of the system should also result in:

1. All floors getting equal service, including the basement, if required
2. Proper handling of multifloor tenants in office buildings to permit efficient interfloor traffic
3. Appropriate action in emergencies, such as general or local power failure or any type of abnormal car-to-signal operation

32.25 REHABILITATION WORK: PERFORMANCE PREDICTION

The primary reason for rehabilitating an existing elevator system is to improve its operating performance. Traction machinery has extremely long life, particularly in the gearless configuration. Thus, the usual rehabilitation project consists of replacing the m-g set, car control panel, and group controller with solid-state, microprocessor-controlled programmable equipment, while retaining the original traction equipment. The car door operator, which controls door action, is usually also replaced because door opening and closing characteristics are an important factor in overall trip time and therefore in system performance.

Major manufacturers have developed computer-based elevator system simulators. Such programs enable architects and owners to input design (or as-is) building data, and to receive graphic and text output on the performance of proposed systems. Because such programs are interactive, the user can change the input data and the characteristics of the proposed equipment until the desired performance level is reached. These programs are particularly useful in modernization work because the owner sees in advance the operation of a proposed system *in his/her building* and can make appropriate decisions based upon good information.

32.26 LOBBY ELEVATOR PANEL

The traditional lobby elevator control and information panel for each elevator bank, which was usually wall-mounted adjacent to the related elevators, has become one or more computer monitor screens positioned at a lobby desk and/or in the building maintenance office. In addition, an information-only screen is frequently wall-mounted adjacent to the related elevators for the edification of waiting passengers.

The information displayed on the screen includes car locations, movement direction, waiting corridor calls, and any special status data. The control functions available at the computer terminal permit intervention to establish special types of operation including:

- Car movement without operating the usual audible and visual signals (*inconspicuous riser*)
- One or more cars removed from supervisory control and operated manually (*attendant or independent service*)
- Cars selected for night or weekend service while the other cars are shut down
- Car(s) assigned to a particular floor on a fixed- or priority-basis call (*convention feature or priority*)

Among other control functions are those concerned with emergency service, including the "fireman's return" feature required by ANSI and many local fire codes (Section 32.46) and the controls related to switching of power between cars in the event that operation on emergency generator power is necessary (Section 32.45).

In addition, means of two-way communication with each car and other selected locations are provided at the control center.

32.27 CAR OPERATING PANEL

A typical car operating panel is illustrated in Fig. 32.17. Every car panel (station) is equipped with full-access buttons for call registry, door-open, alarm, emergency stop, and firefighter control. Also always provided is an intercom device that permits communication with the building control office. A door-close button is sometimes provided if extensive hand operation of the car is anticipated. It is activated only when the car is under manual control. Controls that do not concern the normal passenger are grouped in a locked compartment in the car panel. These include a hand-operation switch; light, fan, and power switches; and any special controls such as security and emergency devices. Finally, a compartment accessible only to technicians contains the devices controlling door motion, car signals, door and car position transducers,

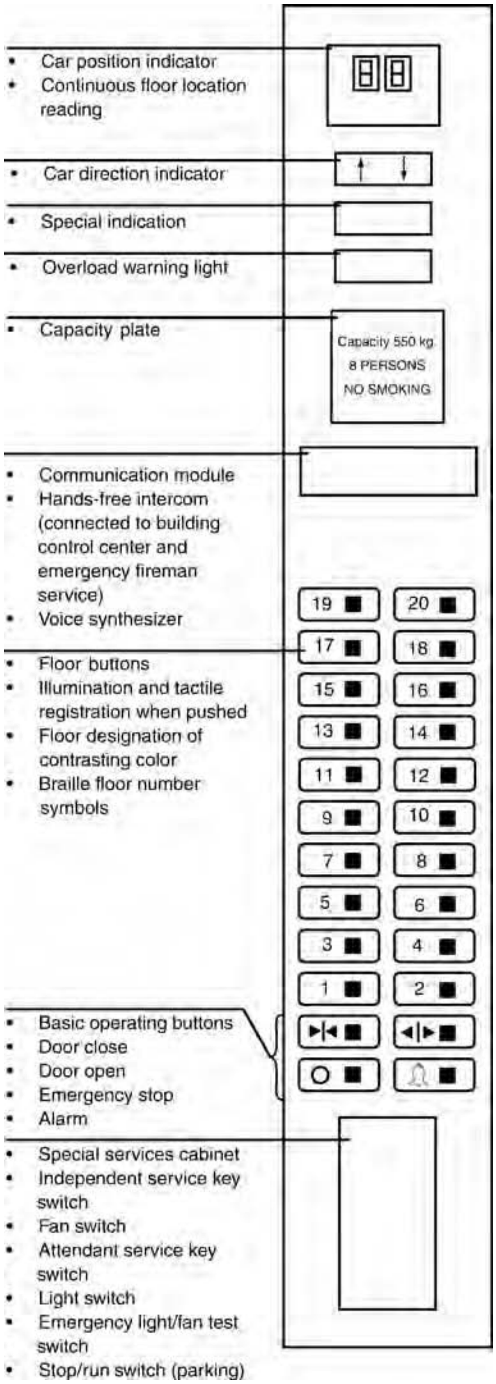


Fig. 32.17 *Typical car operating panel. Designs of these panels vary widely, but the essential components are as shown.*

load-weighing control, door and platform detection beam equipment, speech synthesizer (if used), and visual displays.

ELEVATOR SELECTION

32.28 GENERAL CONSIDERATIONS

The selection of elevators for any but the simplest buildings requires the simultaneous consideration of several factors: adequate elevator service for the intended building usage, economics, and the architectural integration of spaces assigned to elevators, including lobbies, shafts, and machine rooms. In large buildings, many combinations are possible because these factors are interdependent. The selection of an optimum system for such buildings is most practical and accurate with the aid of a computer or simulator, and their use has become standard practice in the industry. Hand computation, following certain guidelines, can yield good results for small, straightforward buildings and reliable preliminary data for almost all buildings.

The design criteria usually used in determining elevator service quality are

- Interval and average waiting time
- Handling capacity
- Travel time

The elevator system selection process, either by hand or computer, involves matching these three criteria with estimated performance values. Design intent (for example, acceptable service or excellent service) will inform the choice of numeric values for the criteria.

32.29 DEFINITIONS

Definitions of important terms, including variant usages, follow.

Average lobby time or average lobby waiting time. The average time spent by a passenger between arriving in the lobby and leaving the lobby in a car. This is a key selection criterion.

Handling capacity (HC). The maximum number of passengers that can be handled in a given time period—usually 5 minutes, thus the term *5-minute handling capacity*. When expressed as a percentage of the building's population, it is called *percent handling capacity* (PHC). This is a key selection criterion.

Interval (I) or lobby dispatch time. The average time between departures of cars from the lobby.

Registration time. Waiting time at an upper floor after a call is registered.

Round-trip time (RT). The average time required for a car to make a round trip—starting from the lower terminal and returning to it. The time includes a statistically determined number of upper-floor stops in one direction and, *when calculating elevator requirements based on up-peak traffic*, an express return trip.

Travel time or average trip time (AVTRP). The average time spent by passengers from the moment they arrive in the lobby to the moment they leave the car at an upper floor. This is a key selection criterion.

Zone. A group of floors in a building that is considered as a unit with respect to elevator service. It may consist of a physical entity—a group of upper floors above and below which are blind shafts—or it may be a product of the elevator group control system, changing with system needs.

32.30 INTERVAL OR LOBBY DISPATCH TIME AND AVERAGE LOBBY WAITING TIME

In an ideal installation, at least from the riding public's point of view, a car would be waiting at the lower terminal on the rider's arrival or would be available after a short wait. Because cars leave the lobby separated in time by the *interval* (*I*) and passengers arrive at the lobby in random fashion, the average waiting time in the lobby should be half (50%) the interval. Field measurements show, however, that it is actually longer than this. The figure most often used in the industry is 60%—that is,

$$\text{Average lobby waiting time} = 0.6 \times I$$

Table 32.4 lists intervals and suggested values for office buildings and the related average waiting time based on the foregoing relationship. Because some control systems zone the building in such a way that some cars do not return to the lobby, the interval as a figure of merit may be somewhat misleading in such buildings. The table also lists recommended intervals for other types of buildings.

TABLE 32.4 Recommended Elevator Intervals and Related[a] Lobby Waiting Time

Facility Type	Interval (sec)	Waiting Time[a] (sec)
OFFICE BUILDINGS		
Excellent service	15–24	9–14
Good service	25–29	15–17
Fair service	30–39	18–23
Poor service	40–49	24–29
Unacceptable service	50+	30+
RESIDENTIAL		
Prestige apartments	50–70	30–42
Middle-income apartments	60–80	36–48
Low-income apartments	80–120	48–72
Dormitories	60–80	36–48
Hotels—first quality	30–50	18–30
Hotels—second quality	50–70	30–42

[a]Based on the relationship: waiting time = 0.6 × interval.

With intervals in the recommended range, riders are not conscious of any irksome delay in elevator service. Consciousness of delay is considered a major drawback in rental desirability and should be avoided for all traffic conditions except morning and evening peaks, when a certain delay is expected and therefore tolerated, however grudgingly. Even in peak periods, any modern group supervisory system will recognize a *timed-out* call—that is, a call with a registration time exceeding 50 seconds—as a priority call. Priority calls are answered by the first available car, usually within 15 seconds. If a considerable amount of interfloor traffic is expected during peak periods, as may be the case when a large company occupies several floors of a building, elevator capacity should be increased by 20% to 40% over the capacity otherwise calculated, to maintain proper intervals.

32.31 HANDLING CAPACITY

The frequency, or interval, with which a car appears at the main building lobby is one of the two factors that determine the passenger capacity of an elevator system. The other is the size of the elevator car. The system's *handling capacity* is completely determined by these two factors—car size and interval—and is independent of the number of cars. This can be best understood by visualizing an elevator system as a single set of doors that opens periodically (the interval) to remove a given number of passengers (the car capacity) from a patiently waiting group of would-be passengers. Whether the set of doors represents a single car or many cars that take turns is immaterial. The only factors that determine the handling capacity are passenger load (car capacity) and frequency of loading (interval) (Table 32.5).

Note is taken of the fact that during peak traffic periods, cars are not loaded to maximum capacity but typically only to about 80%—a figure determined by actual count in many existing installations.

As a convenient measure of capacity, the handling capacity of a system for 5 minutes is taken as a standard. This is because a 5-minute rush period is historically used as a measure of a system's ability to handle traffic. This may be expressed thus:

$$\text{handling capacity } (HC) = \text{passengers/car} \times \text{cars/sec} \times 5 \text{ min} \times 60 \text{ sec/min}$$

Because the number of cars per second is the reciprocal of the interval (e.g., 30 seconds between cars is the same as 1⁄30th of a car per second), this equation reduces to

$$HC = \frac{\text{passengers/car}}{\text{interval} \times 300}$$

or

$$HC = \frac{300p}{I}$$

TABLE 32.5 Car Passenger Capacity (*p*)

Elevator Capacity lb (kg)	Maximum Passenger Capacity	Normal Passenger[a] Load per Trip
2000 (907)	12	10
2500 (1134)	17	13
3000 (1361)	20	16
3500 (1588)	23	19
4000 (1814)	28	22

[a]The number of passengers carried on a trip during peak conditions is approximately 80% of the car capacity.

TABLE 32.6 Minimum Percent Handling Capacities (PHC)

Facility	Percent of Population to Be Carried in 5 Minutes
OFFICE BUILDINGS	
Center city	12–14
Investment	11.5–13
Single-purpose	14–16
RESIDENTIAL	
Prestige	5–7
Other	6–8[a]
Dormitories	10–11
Hotels—first quality	12–15
Hotels—second quality	10–12

[a]Due to more urgent traffic demands, particularly at the school and work exodus.

where *p* is car loading (number of passengers/car). When the interval is 30 seconds, the system's handling capacity is 10*p*, a convenient figure to remember.

To establish a figure of merit for building service, system *HC* must be related to building size. This is normally done by establishing the minimum percentage of the building population that the system must handle in 5 minutes, called PHC. A good system for a diversified office building will handle no less than 12% of the building population. Similar values are shown in Table 32.6 for various types of facilities.

In planning a building's elevator requirements, its population must be estimated. This is particularly difficult in speculative-type, diversified-use buildings. However, based on rental cost, area, and building type, a fair estimate can be made. Population estimates for office buildings are based upon net area—that is, actual available area for tenancy. Table 32.7 gives suggested density figures, and Table 32.8 gives average office building efficiency values for use in calculating net area.

32.32 TRAVEL TIME OR AVERAGE TRIP TIME

The average trip time (or time to destination) is the sum of the lobby waiting time plus travel time to a median floor stop. Car round-trip time is also used as a performance criterion, but it is not as meaningful as trip time. In a commercial building

TABLE 32.7 Population of Typical Buildings for Estimating Elevator and Escalator Requirements

Building Type	Net Area
OFFICE BUILDINGS	FT^2 PER PERSON (M^2/PERSON)
Diversified (multiple tenancy)	
Normal	110–130 (10–12)[a]
Prestige	150–250 (14–23)
Single tenancy	
Normal	90–110 (8–10)
Prestige	130–200 (12–19)
HOTELS	PERSONS PER SLEEPING ROOM
Normal use	1.3
Conventions	1.9
HOSPITALS	VISITORS AND STAFF PER BED[b]
General private	3
General public (large wards)	3–4
APARTMENT HOUSES	PERSONS PER BEDROOM
High-rental housing	1.5
Moderate-rental housing	2.0
Low-cost housing	2.5–3.0

[a]Density may vary for different floors. Clerical and stenographic areas may have a population density as high as 70 ft^2 (6.5 m^2) per person.

[b]If visiting hours are restricted, the visitor population will determine elevator requirements. If visiting is not restricted to a certain few hours, staff requirements may determine elevator design. Where traffic is heavy, a combination of passenger cars and larger "hospital" cars should be used to provide optimum service.

context, a trip of less than 1 minute is highly desirable, a 75-second trip is acceptable, a 90-second trip is annoying, and a 120-second trip is the limit of toleration. In the more relaxed atmosphere of a residence, where interval alone can account for a minute or more of trip time, these maxima are revised upward.

Figure 32.18 shows that the 2000- and 2500-lb (907- and 1134-kg) cars used in residential buildings can have a 17-story rise, even with a 60-second interval, without excessive trip time. The 3500-lb (1588-kg) car, however, which is almost universally used in office buildings (Fig. 32.19), is limited to a maximum 16-floor local run before exceeding the 90-second limit and to about 6 to 8 floors to stay within the 75-second criterion.

An important reservation on the foregoing statements must be noted. The curves presented in Figs. 32.18 and 32.19 are based upon statistical calculations, empirical data, and field observations, as discussed in the next section. This being so, the average values that these curves give should be considered to be ±15% accurate, and borderline cases can be shifted either way. Designs that show high travel time on paper frequently work out well in the field, because lobby loading is often less than 80%, upper-floor stops take less than the statistically predicted time due to groups of people going to the same floor, and staggered working hours relieve traffic peaks. Also, a feature called *high-call reversal* takes account of the fact that cars do not travel to the top of the shaft on each trip, but reverse at the topmost call. This can reduce the average trip time by 5% to 10%. Finally, sophisticated solid-state traffic controls allow for rapid acceleration and deceleration without discomfort, variable door-closing time, and very efficient selection of landing call responses, all of which can further reduce the trip time by another 5%.

TABLE 32.8 Office Building Efficiency

Building Height	Net Usable Area as Percentage of Gross Area
0–10 floors	Approximately 80%
0–20 floors	Floors 1–10 approximately 75%
	11–20 approximately 80%
0–30 floors	Floors 1–10 approximately 70%
	11–20 approximately 75%
	21–30 approximately 80%
0–40 floors	Floors 1–10 approximately 70%
	11–20 approximately 75%
	21–30 approximately 80%
	31–40 approximately 85%

Source: Reprinted from G. R. Strakosch, *Vertical Transportation, Elevators and Escalators*, 2nd ed. John Wiley & Sons, New York, 1983.

Note: Applicable to buildings with 15,000 to 20,000 gross square feet (1394–1858 m^2) per floor.

32.33 ROUND-TRIP TIME

The value for round-trip time during up-peak traffic conditions, used for calculating elevator requirements, is composed of the sum of four factors: (1) time to accelerate and decelerate, (2) time to open and close doors at all stops, (3) time to load and unload, and (4) running time (Figs. 32.20–32.22). Physically, round-trip time is the time from door opening at the lower terminal to door opening at the same terminal at the end of a round trip. Because the actual number of stops made by a car is unknown, a statistical probability value is used, based upon the passenger

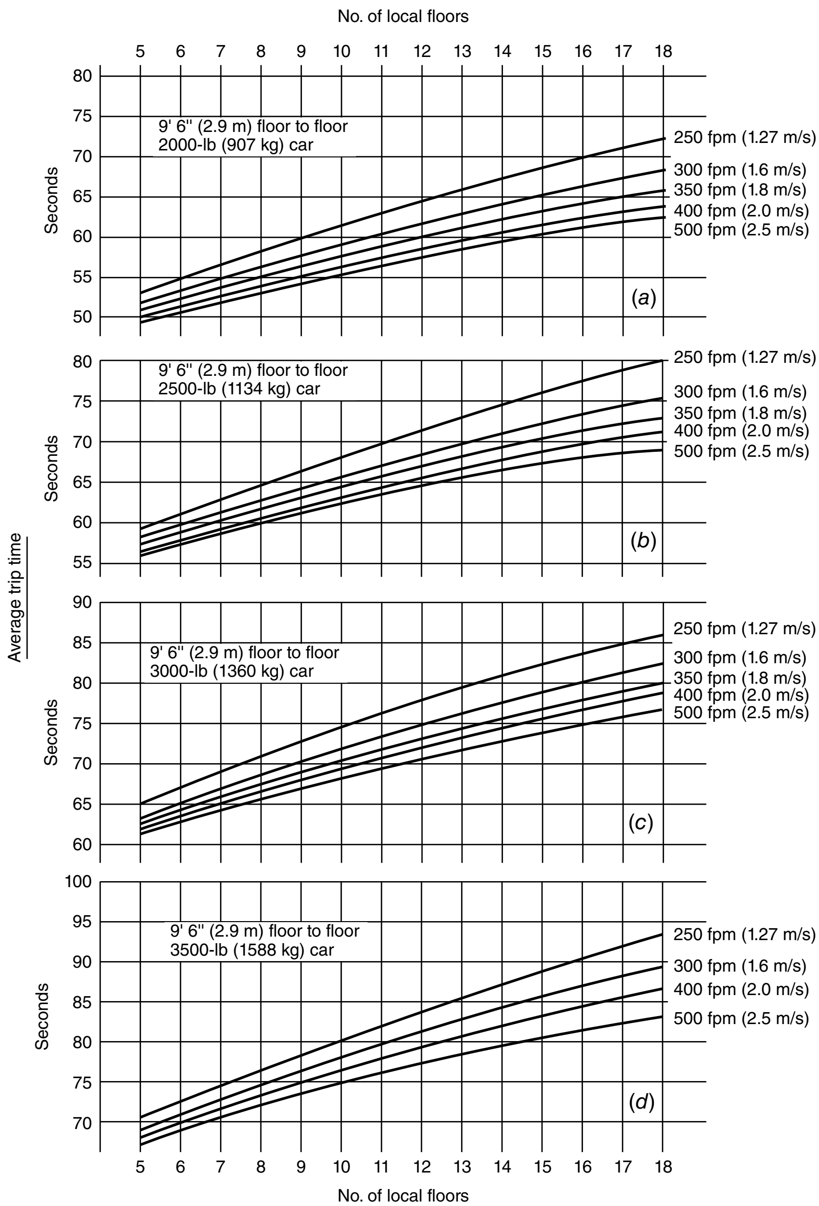


Fig. 32.18 *Plots of average trip time for various car speeds and capacities with a 9-ft, 6-in. (2.9-m) floor height and a 30-second interval.*

capacity of the car and the number of local floors above the lower terminal. In calculating this round-trip time (*RT*), it is assumed that a car will depart the lower terminal when loaded. No intentional delay is included at either the lower or upper terminal. The *RT* thus calculated is a median figure, with any single actual round trip taking more or less time. In detail, *RT* consists of the time expended in

1. Loading at the lobby
2. Door closing at the lobby
3. Accelerating from the terminal and from each stop

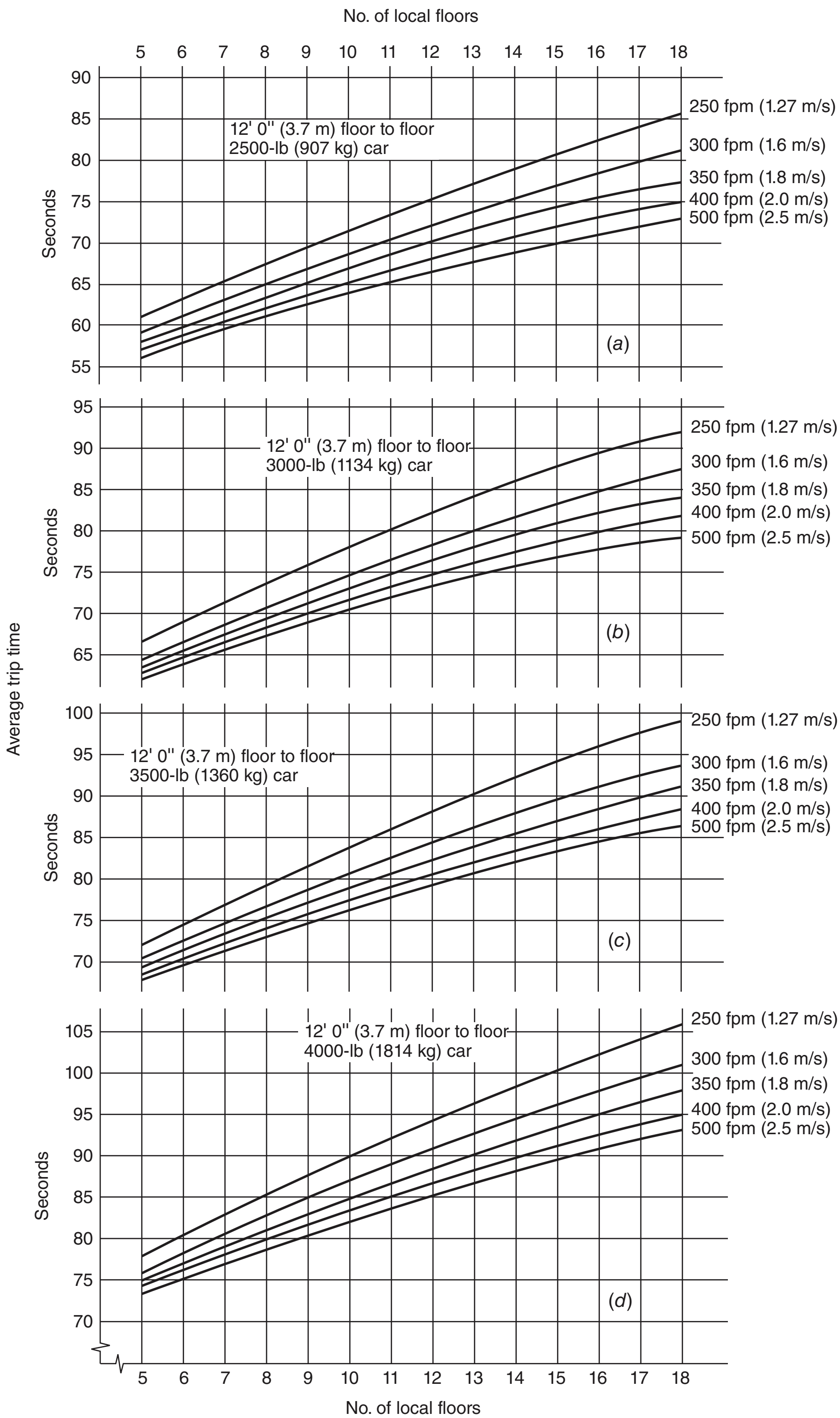


Fig. 32.19 *Plots of average trip time for various car speeds and capacities for a 12-ft (3.7-m) floor height and a 30-second interval.*

4. Decelerating at each stop
5. Passenger transfer at each stop
6. Door operations at each stop
7. Running time at rated speed between stops
8. Return express run from the last stop

These figures are obtained as follows:

1. *Field observations:* Items 1 and 5 are based upon a 3-ft, 6-in. (1.07-m) door opening. A smaller door opening increases passenger transfer time.
2. *Calculations:* Items 2, 3, 4, 6, 7, and 8. *Door-closing time* is based on a 3-ft, 6-in. (1.07-m) center-opening door with adjustable speed.

Acceleration and deceleration times are calculated with a maximum of 4 ft/s/s (1.2 m/s/s) because anything beyond that results in physical discomfort to the passengers. *Running time at rated speed* takes place after the car has accelerated and before it begins to decelerate. Considering that it takes between 20 and 30 ft (6–9 m) to accelerate to 700 fpm (3.6 m/s), depending upon the rate of acceleration, in local runs a car never gets to the rated speed. It simply accelerates and decelerates. Higher-speed equipment with a larger motor accelerates more quickly and gives some time advantage on the return express run, but it has no great time advantage over all. This accounts for the small reduction above 500 fpm (2.5 m/s) seen in Figs. 32.20 and 32.21.

In calculating *RT* for cars in upper zones, it is necessary to know the time required to traverse the express floors. This may be obtained from Fig. 32.22. The times given there are for *one-way* express runs. Thus, to calculate *RT* for an upper-zone car, take the *RT* corresponding to the upper local floors and add *twice* the figure obtained for express run time from Fig. 32.22.

32.34 SYSTEM RELATIONSHIPS

The symbols that will be used in describing elevator calculations are:

p	individual car capacity, equal to 80% of the maximum during peak hours
h	5-minute capacity of a single car
N	number of cars in a system
HC	system 5-minute handling capacity, expressed in number of persons
RT	round-trip time, in seconds
$AVTRP$	average trip time, in seconds
I	interval, in seconds
D	population density, in square feet (m^2) per person
PHC	percent of the population to be moved in 5 minutes, and expressed as a percentage

Now that the definitions of interval, handling capacity, average trip time, and round-trip time have been presented, the interrelationships among these quantities can be demonstrated, along with other equations governing the remaining factors that define elevator systems.

Handling capacity *HC* is determined by car capacity *p* and interval *I:*

$$HC = \frac{300p}{I} \tag{32.1}$$

In a system consisting of a single car, the interval (*I*) is equal to the round-trip time (*RT*). In a system with more than one car, the interval is reduced in proportion to the number of cars. Thus,

$$I = \frac{RT}{N} \tag{32.2}$$

The 5-minute handling capacity (*h*) of a single car is then

$$h = \frac{300p}{RT} \tag{32.3}$$

remembering that for a single car, its interval is its round-trip time. It follows that if the handling capacity of a single car is *h*, then the handling capacity of *N* cars is *N* times as much. Thus,

$$HC = N \times h$$

or

$$N = \frac{HC}{h} \tag{32.4}$$

32.35 CAR SPEED

The selection of car speed to be used is a matter of trial and error, the final selection being that required to give an *RT* that in turn gives an acceptable interval. In order to establish a starting point, however, it has been found that a minimum car speed corresponding to a given building height—or, in elevator parlance, *rise*—can be established. Similarly, although car size can be selected at any value, it has

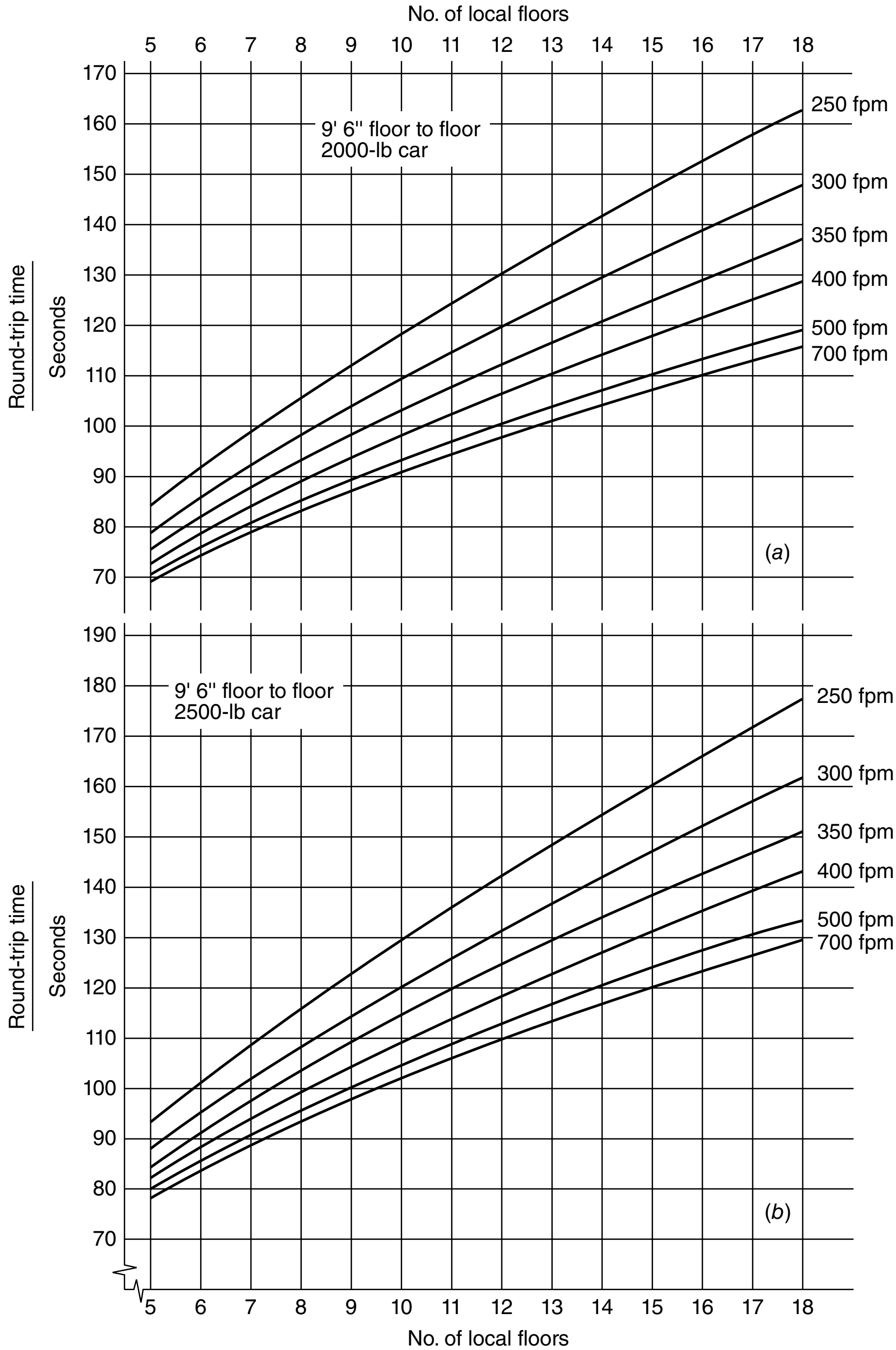


Fig. 32.20 *Plots of round-trip time for various car speeds and capacities with a 9-ft, 6-in. (2.9-m) floor height and a 30-second interval.*

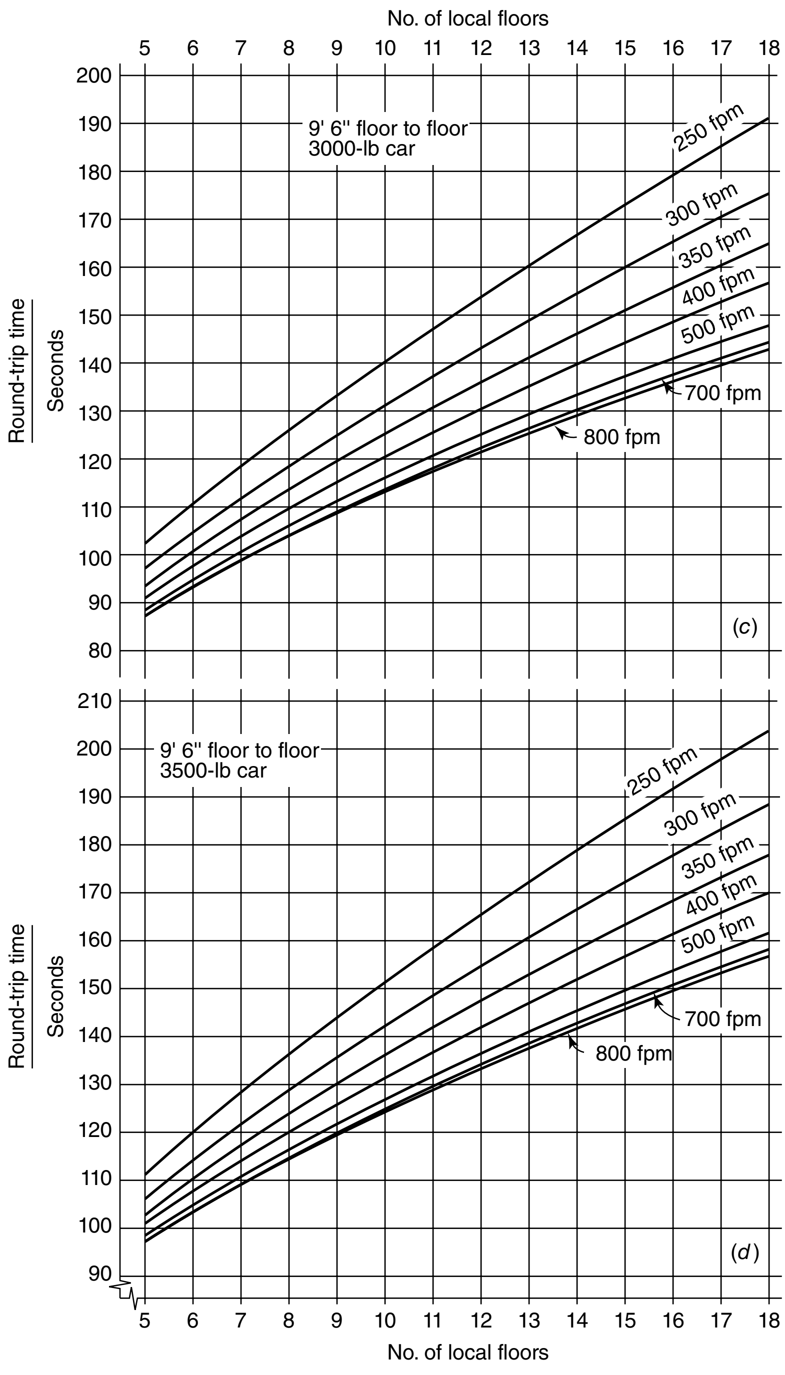


Fig. 32.20 *(Continued)*

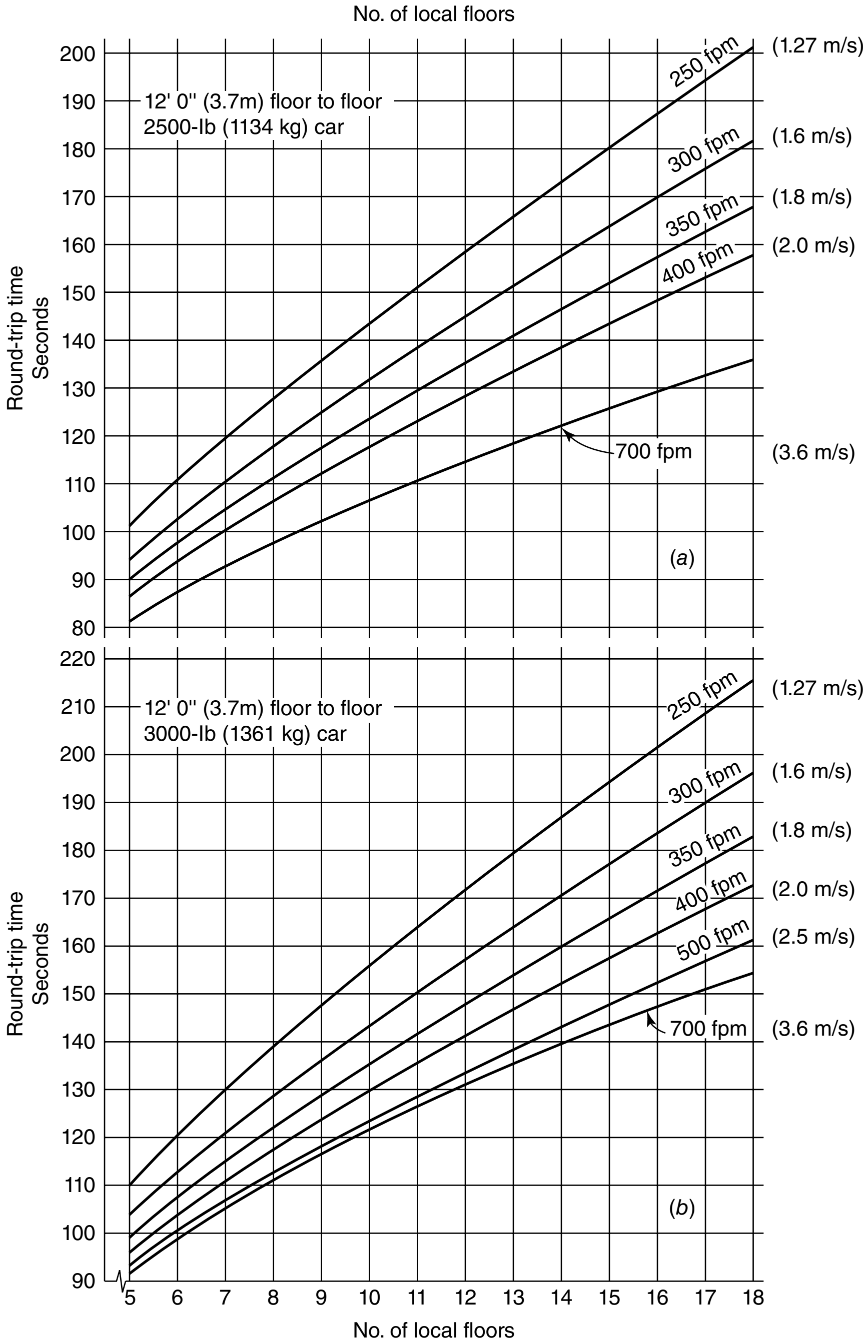


Fig. 32.21 *Plots of round-trip time for various car speeds and capacities with a 12-ft floor (3.7-m) height and a 30-second interval.*

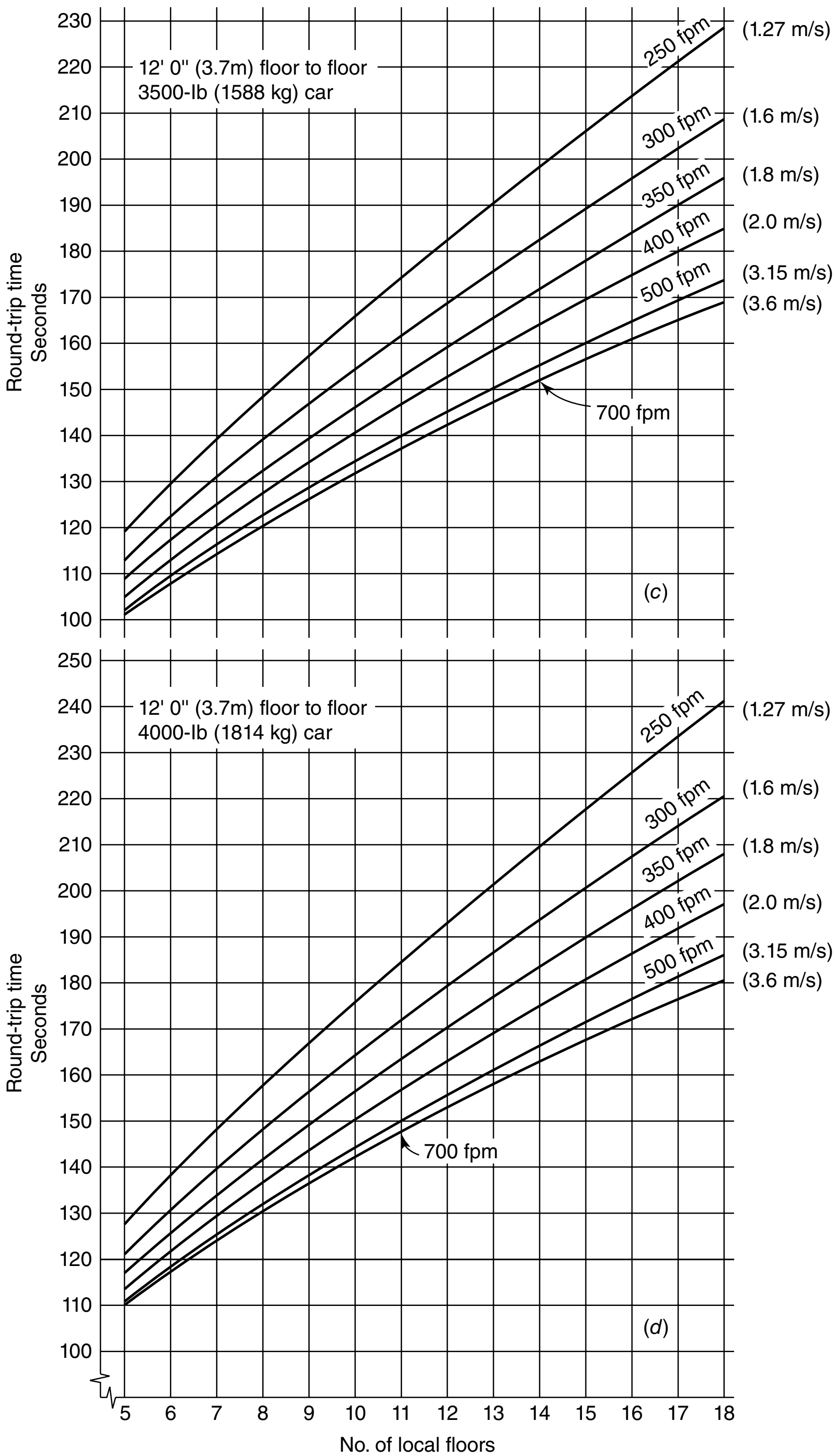
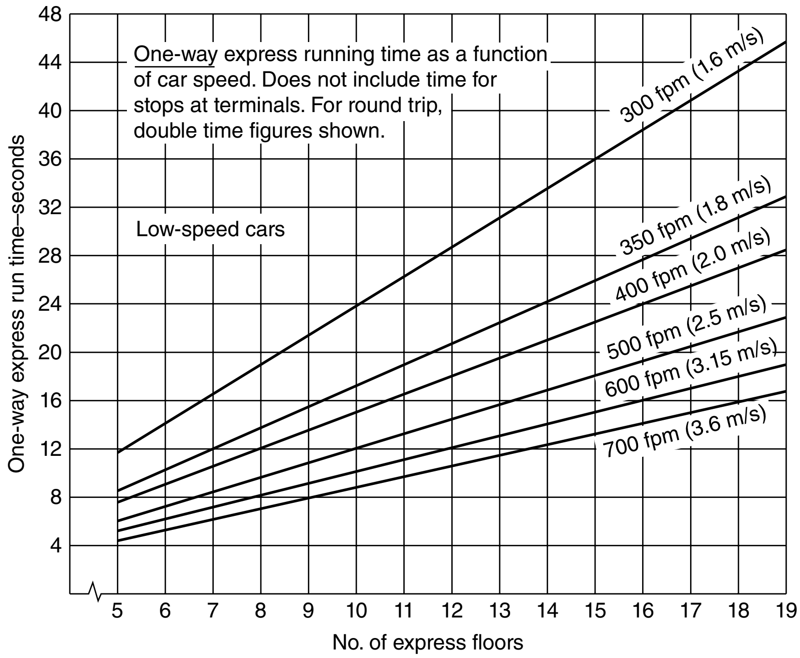
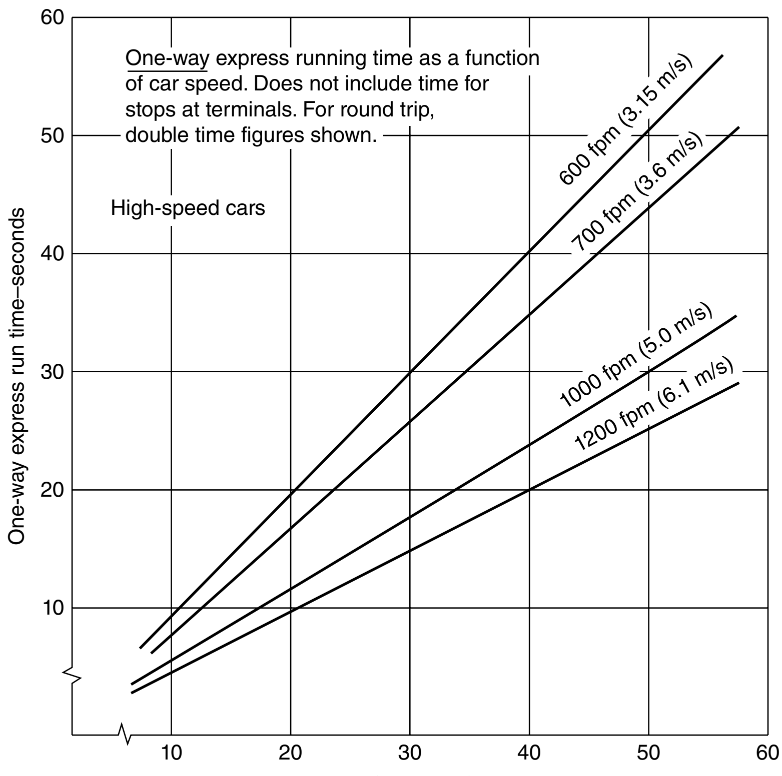


Fig. 32.21 (Continued)



(*a*)



(*b*)

Fig. 32.22 *One-way express running time, not including terminal time; (a) low-speed cars, (b) high-speed cars.*

TABLE 32.9 Elevator Equipment Recommendations

	Car Capacity[a]		*Rise*		*Minimum*[a] *Car Speed*	
Building Type	**lb**	**kg**	**ft**	**m**	**fpm**	**m/s**
Office building	2500 3000 3500	1250 1250 1600	0–125 126–225 226–275 276–375 Above 375	0–40 41–70 71–85 86–115 >115	350–400 500–600 700 800 1000	2.0 2.5 3.15 4.0 5.0
Hotel	2500 3000	1250 1250	As above		As above	
Hospital	3500 4000	1600 2000	0–60 61–100 101–125 126–175 176–250 >250	0–20 21–30 31–40 41–55 56–75 >75	150 200–250 250–300 350–400 500–600 700	0.63 1.0 1.6 2.0 3.15 4.0
Apartments	2000 2500	1000 1250	0–75 76–125 126–200 >200	0–25 26–40 41–60 >60	100 200 250–300 350–400	0.63 1.0 1.6 2.0
Stores	3500 4000 5000	1600 2000 2500	0–100 101–150 151–200 >200	0–30 31–45 46–60 >60	200 250–300 350–400 500	1.0 1.6 2.0 2.5

[a]Car capacity is determined by building size, and car speed by rise.

been shown that for certain facility types, specific-size cars are indicated. These recommendations are given in Table 32.9.

Bear in mind that elevator equipment falls into distinct speed categories. Thus, most manufacturers use geared equipment through 400 fpm (2 m/s) and gearless equipment thereafter. The next category is 500 fpm (2.5 m/s) gearless, followed by 600 fpm (3.0 m/s) to 700 fpm (3.6 m/s), and so on. It is wise to avoid moving into the next higher—and more expensive—equipment category if possible. This may mean exceeding the recommended interval or dropping slightly below desired handling capacity. It will be found, however, that this can usually be done without injury to the elevator system performance, provided that a high-quality group supervisory control system is employed.

32.36 SINGLE-ZONE SYSTEMS

Having established the relationships that govern the design and performance of an elevator system comprising a single zone, it would be helpful to follow through an illustrative example.

EXAMPLE 32.1 Office building, downtown, diversified use, 14 rentable floors above the lobby, each 12,000 ft^2 (1115 m^2) net. Floor-to-floor height—12 ft (3.7 m). Determine a workable elevator system arrangement.

SOLUTION

From Table 32.6, recommended average *HC* is 13%. From Table 32.4, the maximum recommended interval is 25 seconds. From Table 32.7, average population density is 120 ft^2 (11 m^2) per person.

Trial 1
Building population:

$$\frac{14 \text{ floors at } 12{,}000 \text{ ft}^2}{120 \text{ ft}^2 \text{ per person}} = 1400 \text{ persons}$$

$$(14 \text{ at } 1115/11 \approx 1400 \text{ persons})$$

Suggested minimum handling capacity:

$$PHC = 13\%$$

$$HC = 0.13 \times 1400 = 182 \text{ persons}$$

$$\text{rise} = 14 \text{ floors at } 12 \text{ ft } (3.7 \text{ m}) = 168 \text{ ft } (51 \text{m})$$

From Table 32.9, select a car size of 3500 lb (1588 kg) at 500 fpm (2.5 m/s).

3500 lb (1588 kg)

500 fpm (2.5 m/s)

Then, from Figs. 32.23*c* and 32.21*c*:

$$RT = 155 \text{ seconds} \quad AVTRP = 82 \text{ seconds}$$

Single-car capacity: $h = 300p/RT$ (see Table 32.5 for p):

$$h = \frac{300(19)}{155} = 36.8 \text{ persons}$$

$$N = \frac{HC}{h} = \frac{182}{36.8} = 4.9, \text{ say 5 cars}$$

$$I = \frac{RT}{5} = \frac{155}{5} = 31 \text{ seconds}$$

$$\text{actual } PHC = \frac{5(13\%)}{4.9} = 13\%$$

These results are acceptable, but faster cars might reduce the interval. Select 700 fpm (3.6 m/s).

Trial 2

3500 lb (1588 kg)

700 fpm (3.6 m/s)

$$RT = 151 \text{ seconds}$$

$$AVTRP = 81 \text{ seconds (by extrapolation)}$$

$$h = \frac{300(19)}{151} = 37.7 \text{ persons}$$

$$N = \frac{182}{37.7} = 4.8, \text{ say 5 cars}$$

$$I = \frac{RT}{N} = \frac{151}{5} \; 30 \text{ seconds}$$

$$\text{actual } PHC = \frac{5(13\%)}{4.8} = 13.5\%$$

This solution is only marginally better than the previous 500 fpm (2.5 m/s) solution, and the increased cost would not be justified. A trial using smaller cars with shorter *RT* is called for.

Trial 3

3000-lb (1361-kg) cars

500 fpm (2.5 m/s)

$$RT = 143 \text{ seconds} \quad AVTRP = 76 \text{ seconds}$$

$$h = \frac{300(16)}{143} = 33.6 \text{ persons}$$

$$N = \frac{HC}{h} = \frac{182}{33.6} = 5.4 \text{ cars}$$

Using five cars:

$$I = \frac{RT}{N} = \frac{143}{5} = 28.4 \text{ seconds}$$

$$\text{actual } PHC = \frac{5}{5.4}(13\%) = 12\%$$

Trial 4
Using six 3000-lb (1361-kg), 500-fpm (2.5-m/s) cars:

$$I = \frac{RT}{N} = \frac{143}{6} = 23.8 \text{ seconds}$$

and

$$PHC = \frac{6}{5.4}(13) = 14.4\%$$

Both solutions are acceptable.
Tabulating the calculation results, we have:

Solution	Cars lb (kg)	Speed fpm (m/s)	RT (s)	AVTRP (s)	I (s)	PHC (%)
1	5 @ 3500 (1588)	500 (2.5)	155	82	31	13
2	5 @ 3500 (1588)	700 (3.6)	151	81	30	13.5
3	5 @ 3000 (1361)	500 (2.5)	143	76	28.4	12
4	6 @ 3000 (1361)	500 (2.5)	143	76	23.8	14.4

Solutions 1, 3, and 4 are acceptable. Solution 2 was discounted due to the high cost. Interestingly, solution 3, using smaller cars than the corresponding solution 1, and therefore being more economical, gives better results except for *HC*. Although the best solution is number 4, which gives excellent interval and *HC*, the additional cost of a sixth car plus the revenue loss from the rentable area occupied by the sixth shaft and the cost of additional maintenance weigh heavily against this option. A trial with five 3000-lb (1361-kg) cars at 700 fpm (3.6 m/s) is in order, with the knowledge that a considerable cost increase would result because 700-fpm (3.6-m/s) cars require gearless equipment, whereas 500-fpm

(2.5-m/s) cars are available in either geared or gearless format, both giving excellent service.

Trial 5

3000-lb (1361-kg) cars

700 fpm (3.6 m/s)

$$RT = 140 \text{ seconds} \quad AVTRP = 73 \text{ seconds}$$

$$h = \frac{300(16)}{140} = 34.3 \text{ persons}$$

$$N = \frac{182}{34.3} = 5.3; \text{ use 5 cars}$$

$$I = \frac{RT}{N} = \frac{140}{5} = 28 \text{ seconds}$$

$$PHC = \frac{5}{5.3}(13\%) = 12.3\%$$

As expected, improvement over the performance at 500 fpm (2.5 m/s) is very slight: an interval of 28 seconds rather than 28.4 seconds, and a handling capacity of 12.3% versus 12%. The large increase in first cost for gearless equipment would not be justified. ■

At this point, the final selection would be made on the basis of cost. When considering cost, note that first cost is the governing factor only in a speculative venture. With an owner-operator building, the cost comparison should be on a life-cycle basis. Cost figures must reflect the impact of elevator space requirements on net rentable area in the building. Comparative cost figures are given in Table 32.10.

As mentioned earlier, and shown in Fig. 32.16, planners of new buildings today generally take advantage of elevator selection software provided by consultants, by manufacturers, or via in-house capabilities. The results from one such program are shown in Fig. 32.23 (this particular analysis was prepared by Otis Elevator Co.). Note that projected system performance under a variety of operational and functional scenarios can be evaluated and compared.

The round-trip curves in Fig. 32.21 are based on a 3.3-second door time and a 4.0 ft/s^2 (1.2 m/s^2) car acceleration. Note that high call reversal occurs at the top floor (13.6, i.e., 14) and that the number of up stops is 10 (9.7 from statistical calculations). The up-peak calculation assumes no counterflow traffic (i.e., an express down run and no interfloor traffic), as shown. These can be added, however, yielding very different results, as shown in Fig. 32.23. Counterflow traffic (down stops) of only 2% and interfloor traffic of 1%, both of which are reasonable values, change the round trip time substantially and reduce the handling capacity appreciably.

32.37 MULTIZONE SYSTEMS

In general, buildings with fewer than 15 stories are elevatored with a single zone (i.e., all cars serve all floors), and buildings with more than 20 stories are split into two or more zones. Buildings in between these limits—16 to 19 stories—can go either way, depending upon the population density and the

TABLE 32.10 Relative First Cost[a] Figures for Passenger Elevators of Various Speeds and Drive Systems

	Hydraulic fpm (m/s)	*Geared Traction fpm (m/s)*			*Gearless Traction fpm (m/s)*			
Car Size (lb)	**100 (0.63)**	**200 (1.0)**	**350 (2.0)**	**500 (2.5)**	**500 (2.5)**	**700 (4.0)**	**1000 (5.0)**	**1200 (6.0)**
2000 (907)	40	80	100	130	165	170	220	235
2500 (1134)	43	85	115	145	175	180	235	250
3000 (1361)	50	90	120	150	180	185	250	265
3500 (1588)	58	95	125	155	190	195	265	275
4000 (1814)	60	100	135	165	200	205	280	300
4500 (2041)[b]	70	120	150	185	225	230	300	325
5000 (2268)[b]	75	130	160	200	240	250	330	350

[a]Costs are ±10%; based on standard fixtures, cabs, and entrances, and average rise for the speed indicated.

[b]Service elevator or hospital elevator.

Note: See Table 32.9 for speed/rise recommendation.

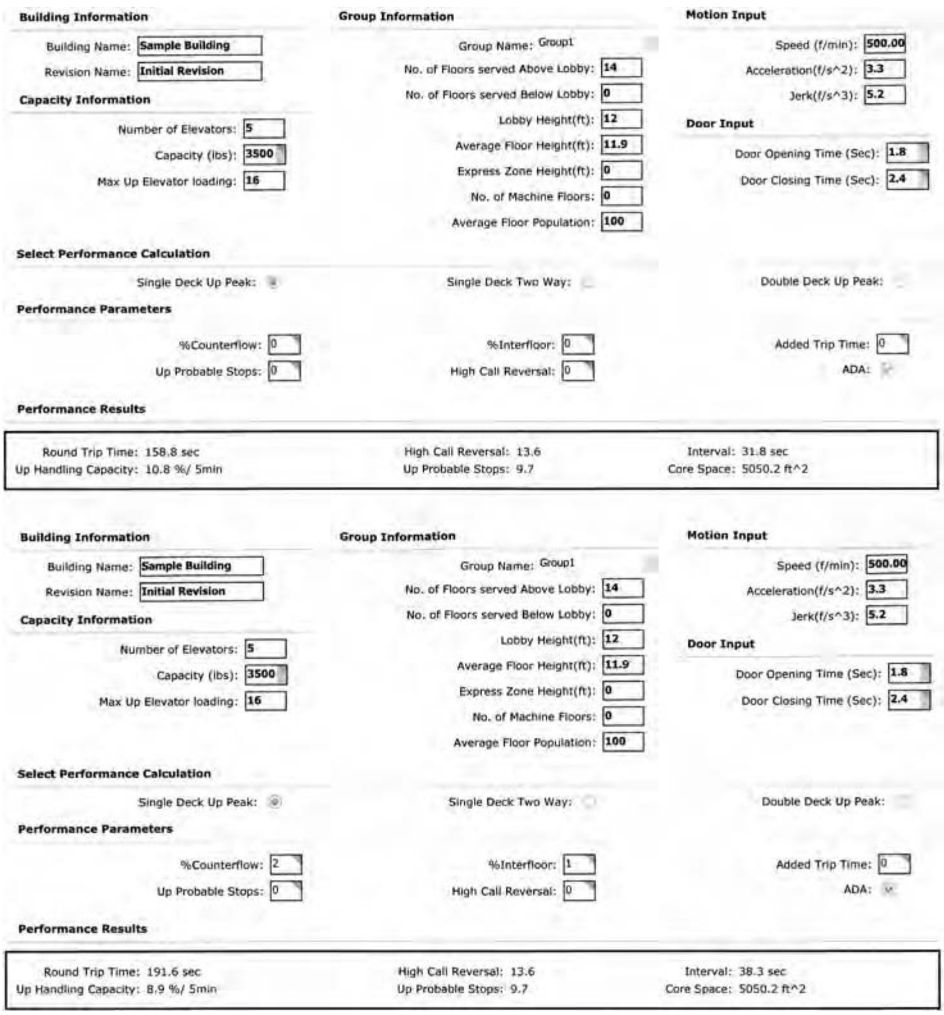


Fig. 32.23 *Printouts from a computerized elevator selection program. This analysis shows that the addition of even light counterflow and interfloor traffic can seriously affect system performance, as can be seen from the round-trip, interval, and handling capacity figures. (Courtesy of Otis Elevator Co.)*

required interval. A modern group supervisory system can automatically zone a building when traffic requires it. Such an arrangement, although efficient, is expensive in terms of both equipment and construction because it does not take advantage of the considerable savings engendered by blind lower shaftways for upper-zone elevators. Analysis of multizone systems is complex and today is rarely done by hand. See Stein et al. (1986) for a detailed explanation of the technique involved. Most designers and consultants use one of many available computerized simulation and selection programs. These have the advantage that, in addition to using basic criteria and building parameters, they can also consider the effect of variations in traffic control. Furthermore, the best of these programs can evaluate the engineering and economic impacts of such factors as varying rental rates for different floors, rental space, machine room and hoistway space, core layout, and the structural ramifications of the elevator system.

32.38 ELEVATOR SELECTION FOR SPECIFIC OCCUPANCIES

(a) Office Buildings

Necessary design criteria can be selected from Tables 32.4 to 32.7. Supervisory group control is normally microprocessor-based. Approximately 1 service car per 10 passenger cars should be provided or, alternatively, one service car for every 300,000 ft^2 (27,870 m^2) of net area. Service cars should be 5000 lb (2268 kg) or larger without a dropped ceiling and, if also used for passenger service, equipped with wall pads. An oversized door (e.g., 4 ft, 0 in. [1.2 m] or 4 ft, 6 in. [1.4 m]) is particularly useful in handling furniture. Service elevators should have a shaftway door at every level plus easy access to the truck dock (or other freight entrance) as well as the lobby. These cars operate as service cars normally but can serve as passenger cars in peak periods to reduce congestion and delay. This fact is particularly useful in marginal service designs. See Table 32.11 for approximate building costs.

(b) Apartment Buildings

Studies indicate that apartment building traffic depends not only upon the population but also on the location and type of tenant. Buildings with many children experience a school-hour peak; buildings in midtown with predominantly adult tenancy exhibit evening peaks due to the homecoming working group and outgoing dinner traffic. Where two cars are required, the second car should function both as a service car and as a passenger car. The cars may be banked or separated, as desired. If a single car is used, it should be of service elevator size.

Self-service collective control is the general choice, with provision for attendant control in prestigious buildings. With small cars and a short rise, a swing-type manual corridor door is acceptable; in larger installations, both the car and the corridor door should be the power-operated sliding type.

Service elevators must be large enough to handle bulky furniture and should therefore be at least 4000 lb (1814 kg), with a 48-in. (1.2-m) door and a high ceiling. Hoistways must be isolated from sleeping rooms by lobbies or other space. Similarly, machine rooms must be isolated because the starting and stopping of motors and other machine room noises are a detriment to sound sleep. Security arrangements are discussed in Section 32.47.

TABLE 32.11 Office Buildings: Cost of Elevator and Electric Work

	Number of Stories		
Item	**20**	**35**	**60**
Elevator work	10.9%	11.9%	12.2%
Electric work	13.3%	12.6%	12.2%

(c) Hospitals

As mentioned in Table 32.7, the governing factor in the determination of elevator requirements may be either normal hospital traffic or visitor traffic, depending upon the visiting-times schedule. Due to the large volume of vehicular traffic such as stretcher carts, wheelchairs, beds, linen carts, and laundry trucks, hospital elevator cars are much deeper than the normal passenger type. This type of car, when used for passenger service, holds more than 20 persons and therefore gives slow service. For this reason, it is occasionally advisable to utilize some normal passenger cars in addition to hospital-size cars, particularly in large hospitals.

The use of tray and bulk carts in food service imposes a considerable load upon the elevator system before, during, and after meals, and passenger service is seriously disrupted. To reduce this congestion and delay, many architects and hospital administrators prefer the use of dumbwaiter cars or another of the many types of materials-handling systems that can handle a 15½ × 20 in. (394 × 508 mm) food tray. These systems can also be used for transporting pharmaceuticals and other items, and are discussed in Sections 33.14–33.16.

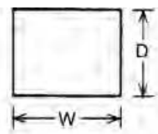
Elevators should be grouped centrally, although separated by type of use. Car control is normally self-service collective.

The population of a hospital may be estimated from Table 32.7. Experience has shown that a carrying capacity of 45 passengers in a 5-minute period is adequate (estimating each vehicle as equivalent to 9 passengers).

Intervals should not exceed 1 minute. All recommendations regarding service for the disabled should be adopted (see Section 32.14).

(d) Retail Stores

Retail stores present a unique problem in vertical transportation inasmuch as the objective is partially to transport persons to specific levels and partially to expose the passengers (customers) to displayed merchandise. For this reason, modern stores rely heavily on escalators, with one or two elevators provided for use by staff and handicapped persons. When, for some reason, it is desired to equip a store exclusively with elevators, use the recommendations shown in Table 32.9, calculated for a load of 10% to 20% of the store's population. Control should be automatic, selective collective. Cars are arranged in a straight line to facilitate loading and waiting.



Car size	D	W
2500 lb	70"	8' 6"
3000 lb	7' 6"	8' 6"
3500 lb	8' 2"	8' 6"
4000 lb	8' 2"	9' 6"

(*a*)

Car size kg	speed m/s	D mm	W mm
1000	2.5	2200	2400
1250	2.5	2200	2600
1600	2.5	2500	2600
2000	2.5	2500	2600
1000	4.0	2200	2400
1250	4.0	2200	2600
1600	4.0	2500	2600
1250	6.0	2250	2500

(*b*)

Fig. 32.24 *Rough hoistway dimensional data for use in schematic design. (a) I-P elevator sizes and dimensions. (b) SI elevator sizes and dimensions.*

PHYSICAL PROPERTIES AND SPATIAL REQUIREMENTS OF ELEVATORS

32.39 SHAFTS AND LOBBIES

Elevator lobbies and shafts are one of the major space issues with which the architect is concerned. The elevator lobby on each floor is the focal point from which corridors radiate for access to all rooms, stairways, service rooms, and so forth. Such lobbies must be located above each other. The ground-floor elevator lobby (also called the *lower terminal*) must be conveniently located with respect to the main building entrances. Equipment within or adjacent to this area should include public telephones (if provided), a building directory, elevator indicators, and possibly a control desk.

Lobbies should provide adequate area for the peak-load gathering of passengers to ensure rapid and comfortable service to all. The number of people contributing to the period of peak load (15- to 20-minute peak) determines the required lobby area on the floor.

Not less than 5 ft^2 (0.5 m^2) of floor space per person should be provided at peak periods for waiting passengers at a given elevator or bank of elevators. The hallways leading to such lobbies should also provide at least 5 ft^2 (0.5 m^2) per person, approaching the lobby. Under self-adjusting relaxed conditions, density is about 7 ft^2 (0.65 m^2) per person. During peak periods crowding occurs, however, reducing this to 3 to 4 ft^2 (0.3–0.4 m^2) per person. An acceptable compromise is 5 ft^2 (0.5 m^2) per person.

The main lower terminal of elevator banks is generally on the street-floor level, although it may be on a mezzanine level when the elevations of the street entrances vary so that one side of the building is at mezzanine level, whereas another entrance is lower. Such a situation is ideal for the use of escalators, which can economically and rapidly carry large numbers of people between levels, thus making practical and efficient a single main lower elevator terminal. The upper terminal is usually the top floor of the building. Typical dimensional data and lobby arrangements are shown in Figs. 32.24 to 32.26.

32.40 DIMENSIONS AND WEIGHTS

Most manufacturers and elevator consultants will, upon request, supply standard layouts for elevators—including dimensions, weights, and structural loads.

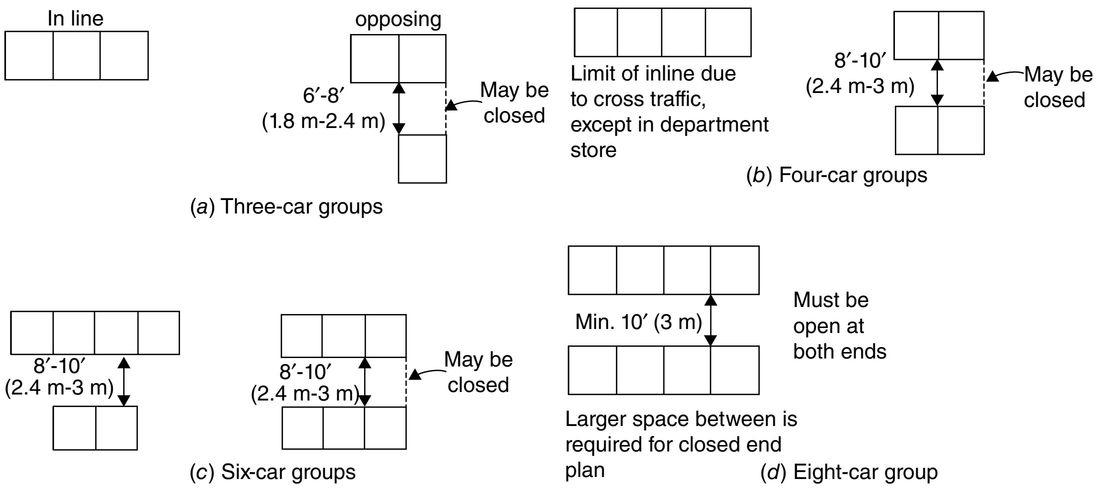


Fig. 32.25 *Lobby groupings for single-zone systems: (a) three-, (b) four-, (c) six-, and (d) eight-car groups.*

Furthermore, to assist in preliminary design, major manufacturers have agreed upon and publish a set of Standard Elevator Layouts via their trade organization, the National Elevator Industry, Inc. (NEII). One such standard is reproduced in Fig. 32.27 for 500- to 700-fpm (2.5–3.6-m/s) gearless units in the full range of car capacities. These standards are available from the NEII.

As may be seen from Fig. 32.27, in providing for an elevator installation it is necessary to consider such factors as the depth of the pit, the dimensions of the hoistway, the clearance from the top of the hoistway to the floor of the penthouse, the size of the penthouse, and the loads that must be carried by the supporting beams.

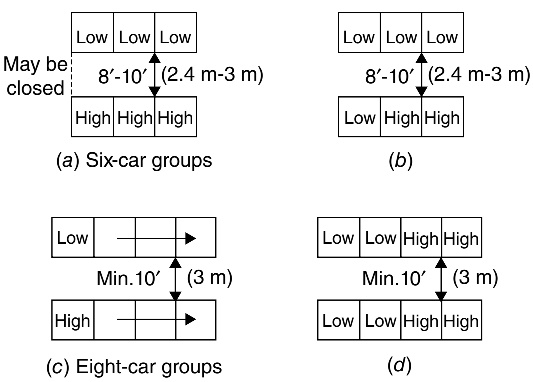


Fig. 32.26 *Lobby groupings for multiple zone systems. Arrangement (a) is preferable to (b), and (c) to (d). Groups with more than four cars in a row are not used because end-to-end walking time would excessively lengthen landing stops and hence total travel time.*

The penthouse floor (and the secondary-level floor, where required) are located above the shaft of each elevator and need approximately 1½ stories of additional height above the top of the support beam of a given elevator when it is standing at its top-floor location. The actual floor area required by the elevator traction machine and its controls is roughly two times the area of the elevator shaft itself. The machine room contains the bulk of the elevator machinery. Because some of this equipment must be moved for maintenance, it is advisable to furnish an overhead trolley beam that can be used during installation as well. The maximum beam load is supplied by the elevator manufacturer.

Some typical machine room dimensional data are listed in Table 32.12, taken from actual installations. Because of multiple drive options and flexibility in equipment arrangements, no general conclusions can be drawn from these figures; they are listed simply to give a general picture of requirements. A manufacturer's layout giving dimensional data for the hoistway and machine room is shown in Fig. 32.28.

When penthouse space is not available and a hydraulic unit is not desired, a basement traction unit, also referred to as an *underslung arrangement*, can be used. These units are always low-speed

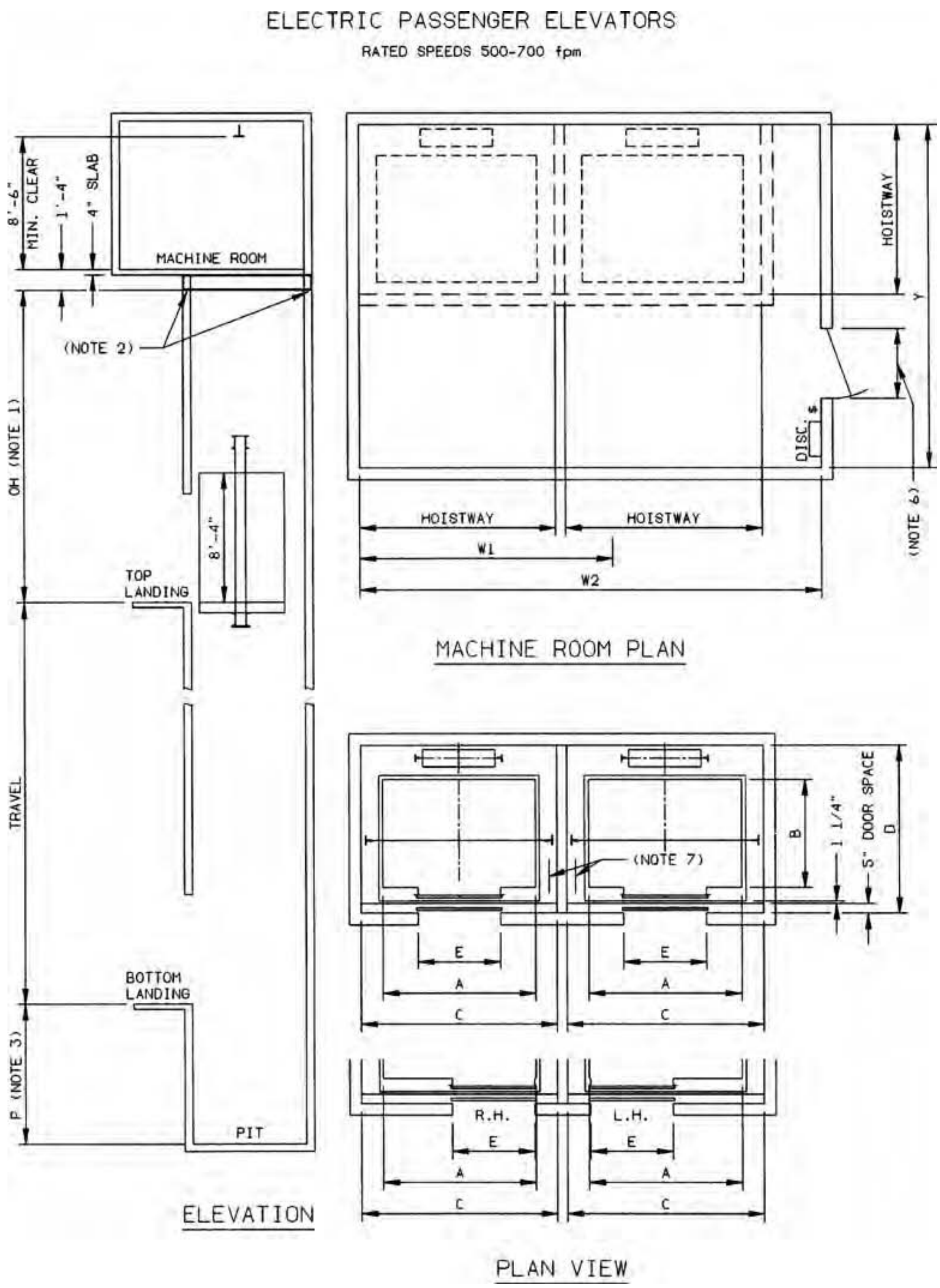


Fig. 32.27 *Typical elevator installation dimensional data. (Reproduced from* Vertical Transportation Standards*, 7th ed., © 1992, with permission of National Elevator Industry, Inc., 185 Bridge Plaza North, Fort Lee, NJ 07024.)*

"OH" BOTTOM OF BEAM (Note 1) ft–in.					
SPEED (fpm)	RATED LOAD (lb)				
	2000	2500	3000	3500	4000
500	17–6	17–6	18–3	18–3	17–6
600	18–6	18–6	18–6	18–6	18–6
700	20–6	20–6	20–6	20–6	20–6

CAR & HOISTWAY								
RATED LOAD (lb)	AREA ■	ft–in. (Note 11)					ENTRANCE (Note 10)	
		A	B	C	D	E	TYPE	
2000	24.2	5–8	4–3	7–4	6–11	3–0	SSSO ▲	SSCO
2500	29.1	6–8	4–3	8–4	6–11	3–6	SSSO ✱	SSCO ▲
3000	33.7	6–8	4–7	8–4	7–5	3–6	SSSO ✱	SSCO ▲
3500	38.0	6–8	5–3	8–4	8–1	3–6	SSSO ✱	SSCO ▲
4000	42.2	7–8	5–3	9–6	8–1	4–0	SSCO ✱	

"P" PIT DEPTH (Note 3) ft–in.					
SPEED (fpm)	RATED LOAD (lb)				
	2000	2500	3000	3500	4000
500	10–1	10–1	10–1	10–1	10–1
600	11–5	11–5	11–5	11–5	11–5
700	11–5	11–5	11–5	11–5	11–5

MACHINE ROOM ft–in.					
RATED LOAD (lb)	W1 WIDTH	W2 WIDTH	"Y" DEPTH FOR RATED SPEED (fpm)		
			500	600	700
2000	7–4	15–0	18–6	18–6	18–6
2500	8–4	17–0	18–6	18–6	18–6
3000	8–4	17–1	18–6	18–6	18–6
3500	8–4	17–1	18–6	18–6	18–6
4000	9–6	19–5	18–6	18–6	18–6

Notes
1. "OH" Dimensions are based on a 8'–4" overall car height.
2. Supports for elevator machine beams not by elevator supplier.
3. For travel greater than 400'–0" increased pit depth may be required. Consult elevator supplier.
4. 3'–6" x 7'–0" Recommended.
5. Pit ladder not by elevator supplier.
6. Dividing beams, not by elevator supplier, to be designed to sustain rail forces. Consult elevator supplier.
7. When compliance with seismic risk zone 2 or greater requirements is anticipated, provide additional hoistway space.

Notes
- ■ Maximum allowable inside car area in ft^2 per ASME A17.1, Rule 207.1.
- ✱ These car dimensions and entrance types provide wheelchair accessibility and accommodate an ambulance type stretcher (76 in. x 24 in.) in the horizontal position.
- ▲ These car dimensions and entrance types provide wheelchair accessibility.

Fig. 32.27 *(Continued)*

TABLE 32.12 Typical Elevator Machine Room Dimensions

Bank Description No. – lb (kg)	fpm (m/s)	Approximate Machine Room Dimensions ft (m)
2–2500 (1134)	125 (0.6)	16 × 18 (4.9 × 5.5)
3–2500 (1134)	350 (1.8)	19 × 26 (5.8 × 7.9)
3–2500 (1134)	700 (3.6)	21 × 26 (6.4 × 7.9)
6–3500 (1588)	500 (2.5)	26 × 29 (7.9 × 8.8)
6–3500 (1588)	700 (3.6)	27 × 27 (8.2 × 8.2)
6–3500 (1588)	1000 (5.1)	27 × 27 (8.2 × 8.2)
6–5000 (2268)	450 (2.3)	31 × 33 (9.5 × 10.1)

(100–350 fpm [0.5–1.8 m/s]) and are therefore applicable only where rise is limited and traffic is light to medium. Figure 32.29 shows a typical shaft section for this design with car and dimensional data.

32.41 STRUCTURAL STRESSES

For structural design, it is necessary to know the overhead load that must be supported by the foundations, by structural columns extending up to

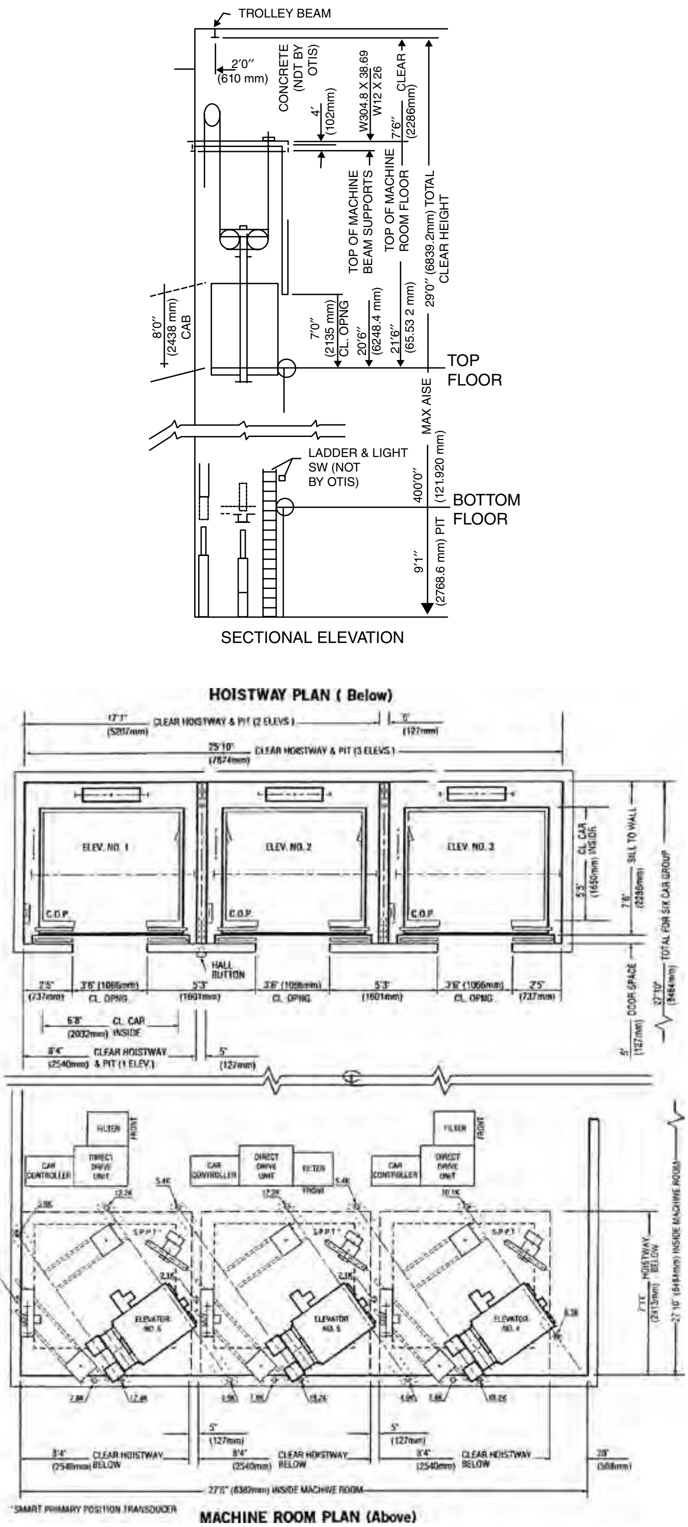
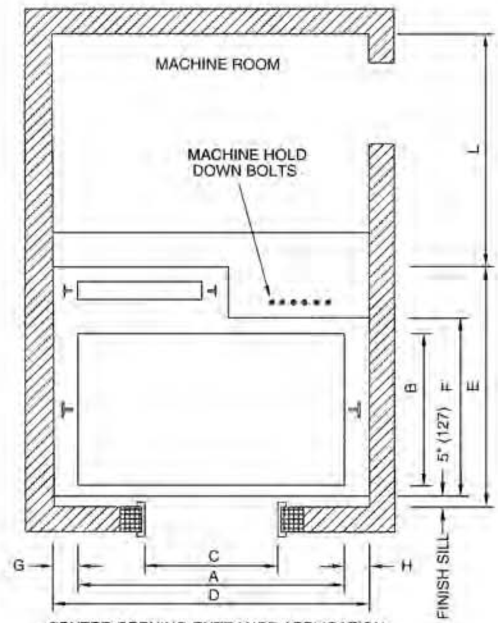
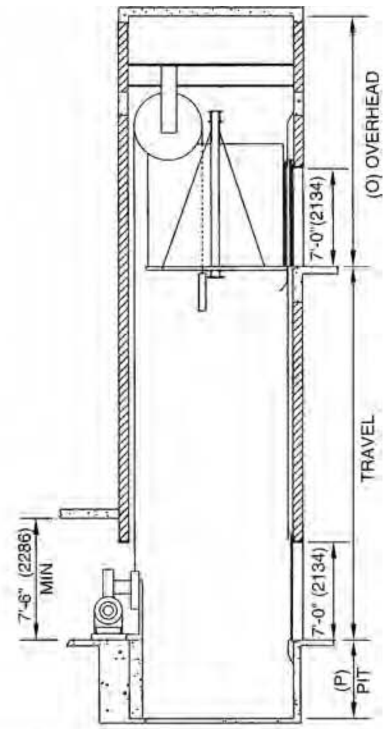


Fig. 32.28 *Manufacturer's layout data for a bank of six 3500-lb (1588-kg), 700-fpm (3.45-m/s) gearless passenger elevators. Equipment shown in the machine room is the thyristor control for DC traction machines. Because each controller provides group supervisory control in this design (Otis Elevonic 411), no separate group supervisory equipment is shown. No additional space would be required if a UMV drive with m-g sets were selected rather than thyristor control. (Courtesy of Otis Elevator Co.)*



CENTER OPENING ENTRANCE APPLICATION
(N/A FOR 2000 LB. CAP.)
(SINGLE SLIDE OPTIONAL)



2:1 ROPING

2:1 ROPING ARRANGEMENT

Overhead dimension is reduced to a minimum. Greater pit depth is required due to the sheave arrangement as compared to a 1:1 installation.

SIZES & CAPACITIES

CAPACITY	2000 lbs. (907 kg)	2500 lbs. (1134 kg)	3000 lbs. (1361 kg)	3500 lbs. (1588 kg)
A	6'-0" (1829)	7'-0" (2134)	7'-0" (2134)	7'-0" (2134)
B	5'-0" (1524)	5'-0" (1524)	5'-6" (1676)	6'-2" (1880)
C	3'-0" (914)	3'-6" (1067)	3'-6" (1067)	3'-6" (1067)
D	8'-0" (2438)	9'-0" (2743)	9'-0" (2743)	9'-0" (2743)
E	6'-10" (2083)	6'-10" (2083)	7'-4" (2235)	8'-0" (2438)
F	5'-4" (1626)	5'-4" (1626)	5'-10" (1778)	6'-6" (1981)
G	1'-0" (305)	1'-0" (305)	1'-0" (305)	1'-0" (305)
H	1'-0" (305)	1'-0" (305)	1'-0" (305)	1'-0" (305)

MINIMUM MACHINE ROOM OVERHEAD & PIT DIMENSIONS

SPEED	100 FPM (0.51 m/s)	200 FPM (1.02 m/s)	250 FPM (1.27 m/s)
L	10'-6" (3200)	10'-6" (3200)	10'-6" (3200)
O	13'-0" (3962)	13'-2" (4013)	13'-7" (4140)
P	5'-6" (1676)	6'-6" (1981)	6'-11" (2108)

NOTES:

1. If a counterweight safety is applied, consult Montgomery KONE
2. Layouts and dimensions shown are for machine located at rear of hoistway.
3. Add 4" (102) to dimension D in seismic zones.
4. Other capacities, speeds, and arrangements are available.

Fig. 32.29 *Typical data for a basement traction machine (underslung) arrangement, used where a penthouse is unavailable or undesirable. (Courtesy of Montgomery-KONE.)*

the penthouse, and by the main beams that support the penthouse floor and subfloor. These loads (reactions) are supplied by manufacturers and usually include the actual dead weights of equipment when the elevator is not in motion, plus the added weight caused by the momentum of all moving parts and passengers when the elevator is at top speed and is suddenly stopped rapidly by the safety devices.

POWER AND ENERGY

32.42 POWER REQUIREMENTS

The power required by an elevator drive is that which is needed to provide the necessary traction and to overcome friction. Because power is equal to the *rate* at which work is done, elevator motor size is directly proportional to the speed of the system. In other words, it requires proportionately more power to lift a 3000-lb (1361-kg) car at 700 fpm (3.6 m/s) than at 200 fpm (1.0 m/s). This relationship is shown in Fig. 32.30, which shows the minimum size of a DC elevator traction motor as a function of speed for cars of different capacity. (For power data on hydraulic elevators, see Section 32.9.) As friction is higher in a geared machine than in a gearless unit, the geared machine traction motor must be larger for the same car speed. The size of the traction machine shown in Fig. 32.30 is independent of the power supply design (m-g set, VVVF, thyristor control) because it is determined purely by traction system requirements. (In practice, however, traction motors with VVVF control are frequently smaller because they operate more efficiently.)

An elevator moves only about 50% of the time, the remainder being spent standing at various landings. As the number of cars in a bank increases, the probability of *all* the cars being in operation simultaneously decreases, resulting in a system demand factor of less than 1.0. The factor for different group sizes is shown in Fig. 32.30.

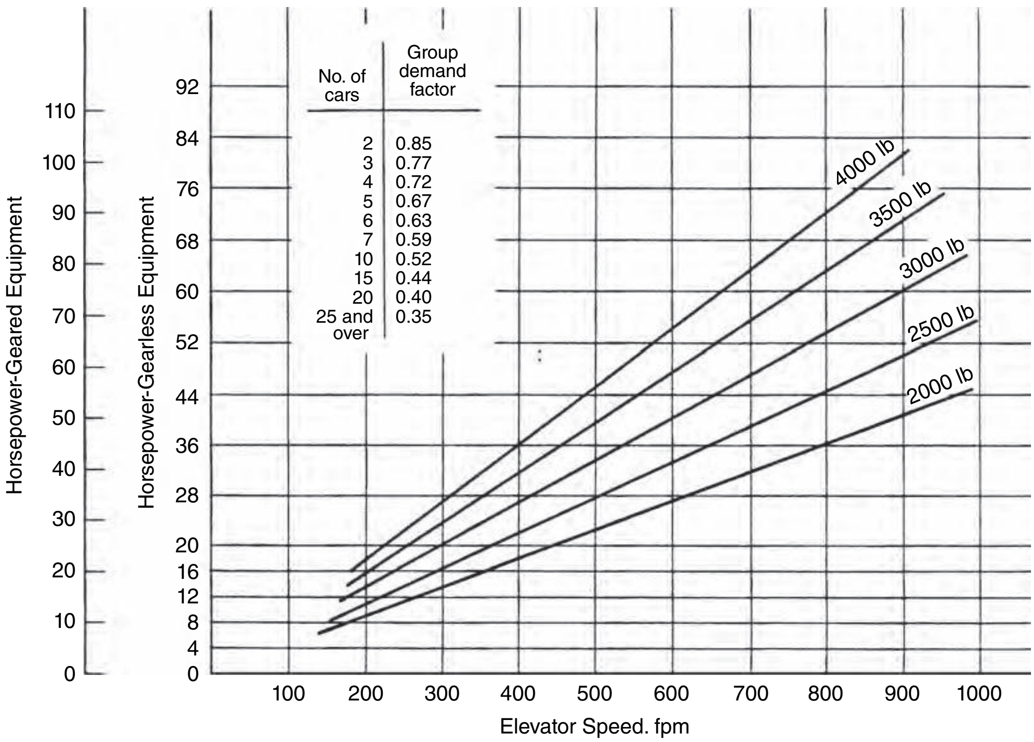


Fig. 32.30 *Elevator traction motor power requirements per car. An m-g set drive (if used) is approximately 20% larger than a traction machine.*

As an example of the use of the power curves, consider a bank of five 3500-lb (1588-kg), 600-fpm (3.0-m/s) units. From Fig. 32.30, each car requires 48 hp (36 kW):

$$\text{group demand factor} = 0.67$$

$$\text{total instantaneous power required}$$
$$= 5 \times 48 \times 0.67 = 160\ \text{hp}$$
$$(= 5 \times 36 \times 0.67 = 120\ \text{kW})$$

Note that this is the *traction motor* power requirements. If an m-g set with an overall efficiency of 80% is used to drive the traction motor, the elevator system power requirement is

$$\text{system power} = \frac{160\ \text{hp}}{80\%\ \text{eff}} = 200\ \text{hp}$$

$$(120\ \text{kW}/0.80 = 150\ \text{kW})$$

which must be provided by the building electrical system. If a solid-state power supply system with a (typical) efficiency of 92% is used, the system power requirement will be only

$$\text{system power} = \frac{160\ \text{hp}}{92\%\ \text{eff}} = 174\ \text{hp}$$

$$(120\ \text{kW}/.0.92 = 130\ \text{kW})$$

which is a 13% reduction from the previously calculated 200-hp (150-kW) requirement.

32.43 ENERGY REQUIREMENTS

The energy used by an elevator is essentially the system friction, including the heat generated by the brakes plus the electrical losses in the traction motor and power supply equipment (rotary or solid-state). The energy expended in raising a car and its passengers is simply stored as potential energy. It is *returned to the power system* when the car and passengers descend via the system of regenerative braking used in almost all elevator systems. Refer to Fig. 32.31, which shows the approximate efficiencies of the components of a typical system. With these data, it is possible to calculate a system's energy consumption.

EXAMPLE 32.2 Given a system of five 3500-lb (1588-kg), 600-fpm (3.0-m/s) gearless cars, calculate:

a. The heat generated in the machine room during peak periods; assume solid-state control
b. The approximate monthly energy cost; using a combined demand/energy rate of \$0.08/kWh

SOLUTION

a. During peak periods, the traction motor operates approximately 50% of the time and is at standstill the other half. Assume that, while operating, it draws 90% of the full load (with a VVVF power supply, this figure is reduced

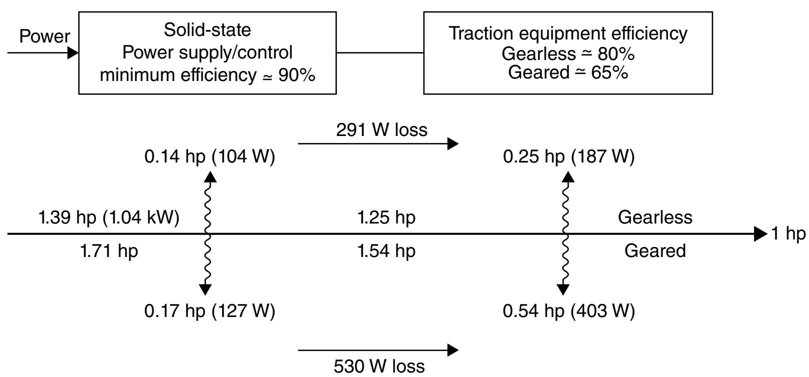


Fig. 32.31 *Block diagram showing losses in the system per horsepower (kW) delivered to the elevator car and the equivalent wattages. Note that the losses in a geared system are almost double those of a gearless one. Figures shown are for solid-state thyristor controls.*

considerably). Therefore, for one car, from Fig. 32.30,

$$\text{traction motor} = 48\ \text{hp}\ (36\ \text{kW})$$

Total loss per machine:
In controls:

$$\frac{48\ \text{hp}}{0.9\ \text{eff}} \times 90\%\ \text{load} \times 50\%\ \text{operation} \times 10\%\ \text{loss}$$
$$= 2.4\ \text{hp}\ (1.8\ \text{kW})$$

In traction motor:

$$48\ \text{hp} \times 90\%\ \text{load} \times 50\%\ \text{operation} \times 20\%\ \text{loss}$$
$$= 4.32\ \text{hp}\ (3.2\ \text{kW})$$

$$\text{total} = 6.72\ \text{hp} = 17{,}100\ \text{Btu/h (equivalent to 5 kW)}$$

Because five elevators are operating, the total heat generated is

$$5 \times 17{,}100\ \text{Btu/h} = 85{,}500\ \text{Btu/h (equivalent to 25 kW)}$$

This is roughly the heating capacity of a home furnace. As a result, machine room temperatures in warm climates frequently reach 120°F (49°C). (No diversity is taken because all the machines are operating and the heating is additive; diversity is applicable only in calculating instantaneous load.)

As solid-state elevator equipment is much less tolerant of high ambient temperatures than the electromechanical switches and relays previously used, an elevator machine room should be held to a maximum dry-bulb temperature of 90°F (32°C). (Temperatures above 90°F (32°C) can result in unreliable elevator system performance.) This limit can sometimes be accomplished by thermostatically controlled forced ventilation, particularly if spill-over air from an air-conditioned space is available. However, because machine rooms are frequently on the building roof and exposed on all surfaces to ambient temperatures and solar radiation, air conditioning may be necessary. It is also important to prevent machine room temperature from dropping below 55°F (13°C). This can usually be done with one or more unit heaters, which will normally operate only during the winter, and then only on nights and weekends.

In actual design situations, accurate heat loss values, which are available from manufacturers, would be used, along with accurate heat gain and heat loss calculations for the specific machine room being designed. Frequently, use of thermal insulation, thermostatically controlled louvers, and sunshading can ease the thermal load and result in appreciable savings in money and energy. Because of the high initial and operating costs of air conditioning, some elevator manufacturers use control components that are tolerant of high temperatures. This point should be carefully examined with proposed elevator equipment manufacturers and the conclusions reflected in the elevator system specifications.

b. To calculate a monthly energy cost, an estimate must be made of the total usage of the system. Assuming the system to be in an office building, a reasonable breakdown of operation during a 24-hour day would be

   2 hours at peak use
   2 hours at 70% of peak
   6 hours at 50% of peak
   14 hours at 10% of peak

This gives a weighted average of 30% of peak load for the elevator bank. Therefore, per car

$$\begin{aligned}\text{energy} &= 30\% \times \text{total losses} \times 24\ \text{hours}\\ &= 0.3 \times 6.72\ \text{hp (or 5 kW)} \times 24\ \text{hours}\\ &= 48\ \text{hp-h (or 36 kW-h)} = 36\ \text{kWh/day/car}\end{aligned}$$

Monthly cost would be

$$\begin{aligned}&36\frac{\text{kWh}}{\text{day}} \times 25\ \text{days} \times \$0.08\\ &= \$72/\text{month/car}\\ &= \$360/\text{month for the bank}\end{aligned}$$

This figure would be lower with a VVVF power supply and higher for a Ward–Leonard (m-g set) arrangement. ■

32.44 ENERGY CONSERVATION

A reduction in energy consumption can be accomplished by implementing the following recommendations:

For Existing Elevators

1. Increase the interval during nonpeak hours.
2. Replace m-g sets with a solid-state DC power supply or AC traction motors with a VVVF power supply. This conserves energy not only

due to the higher efficiency of the power supply, but also because energy consumption of idling machines is eliminated.
3. Reclaim machine room waste heat.
4. Shut down some units completely during off hours.

For a Building in the Planning Stage

1. Base the design on the maximum recommended trip time.
2. Use the lowest speeds possible within a type—that is, geared or gearless.
3. Use gearless equipment whenever possible.
4. After construction, implement the energy conservation recommendations for existing elevators.

Because elevator shafts can induce a powerful stack effect, measures should be taken to counteract the potential loss of heat from the building that may occur during the heating season.

32.45 EMERGENCY POWER

Major power failures and local brownouts have demonstrated forcefully the need for a standby or emergency power source of adequate size to operate an affected building's elevators. Few experiences are so harrowing as being trapped in the crowded confines of a small box suspended in a long vertical shaft, with little or no light, and complete strangers for companions.

A common misconception about elevators is that on failure of power, the cars will automatically descend to the nearest landing, where an exit is then possible. In reality, the car brake is set immediately upon power outage and the car remains stationary. Hydraulic cars can be lowered by operation of a manual valve; *small* traction cars can be cranked to a landing by hand, but large cars are fixed in position. This is particularly bad for cars in blind shafts—that is, express shafts with no shaftway doors. In such cases, escape from the cars via a hatchway is not practical; when emergency power is not available, the undesirable option of breaking through the shaftway walls is the only recourse.

In addition to simple inconvenience, loss of elevator service in facilities such as hospitals and mental and penal institutions constitutes a danger to life. For this reason, most codes require that emergency power be available in specific building types to operate at least one elevator at a time, and for elevator lighting and communications. Many installations separate the emergency power functions, providing a generator for elevator traction power and separate individual elevator battery packs for communications, lighting, and, preferably, the car fan. The last two items can be furnished as an option by elevator manufacturers with their cars.

The generator is normally sized to supply one elevator motor at a time, with manual or automatic switching arranged between unit controllers. Thus, each car in turn can be brought to a landing, and thereafter a single car can be retained in service. If it is desired to operate more than one car, a larger generator can be installed. This might well be the case in a multiwing building with critical service requirements, such as a hospital.

The amount of power required, the size of the emergency generator, and the equipment size necessary to absorb regenerative power are all data that can be furnished by a consulting engineer and the elevator manufacturer.

SPECIAL CONSIDERATIONS

32.46 FIRE SAFETY

Most fire codes specify the procedures that elevator control equipment must implement once a fire emergency has been initiated. Details vary somewhat, but in general the actions are these:

1. All cars close their doors and return nonstop to the lobby or another designated floor, where they park with the doors open. Thereafter, they are operable in manual mode only, by use of the firefighter's key in the car panel.
2. All car and hall calls are canceled, and call-registered lights and directional arrows deactivated.
3. The fire emergency light or message panel in each car is activated to inform passengers of the nature of the alert and that cars are returning to a designated terminal.

4. Door sensors and in-car emergency stop switches are deactivated.
5. Traveling cars stop at the next landing without opening their doors and then proceed to the designated terminal.

The cars can then be used by trained personnel to transport firefighters and equipment and for evacuation. In the event of a false alarm, the emergency procedure can be overridden at the (lobby) control point, and the system can then be returned to normal while the source of the alarm is located. (This is a particularly important feature in large buildings with automatic fire alarm systems containing hundreds of fire, smoke, and water-flow detectors.)

32.47 ELEVATOR SECURITY

Elevator security has two key aspects: physical security of riders and consideration of the elevator as a portal in a building-access security system.

(a) Rider Security

This problem is particularly difficult inasmuch as a traveling elevator is an enclosed space that can be rendered inaccessible simply by pressing the emergency stop button. Thereafter, an attacker can escape at a floor of his/her choice. To reduce this danger (to some extent), elevators are equipped with alarm buttons that alert residents and security personnel (if any). Every elevator, by code, must be equipped with communication equipment. A two-way communication system with "no-hands" operation in the car is particularly effective for security. When a closed-circuit TV monitor is added, utilizing a wide-angle camera in each car (Fig. 32.32), the security problem will have been addressed to a considerable extent. Using a communication and TV system presupposes continuous monitoring of the building security desk so that an incident will be detected.

Fig. 32.32 *Wide-angle camera coverage intended for elevator car surveillance. A prominent printed warning in the car is an integral part of the system's effectiveness.*

(b) Access Control

This is often a matter of restricting access to (and from) a floor or car. This can be accomplished by pushbutton combination locks or coded cards, the proper use of which will permit access (see Chapter 31). However, if a second (unauthorized) person accompanies an authorized person, the effectiveness of this type of access control is seriously compromised. In sum, the most effective security system is a combination of automatic monitoring and access devices coupled with continuous supervision by persons who know the appropriate actions to take in an emergency.

32.48 ELEVATOR NOISE

Elevator operation, with its rotating, sliding, and vibrating masses, can be a cause of serious noise disturbance to quiet areas such as sleeping rooms, libraries, and certain types of office space. Noise and vibration can be reduced by the appropriate application of noise control strategies and vibration isolators (e.g., between guide rails and the structure), but primarily by placing noise-sensitive areas away from shafts and machine rooms. The clatter and whirring sound associated with older machine rooms (and caused by relays, step switches, m-g sets, and sliding contacts) can be entirely eliminated by the use of solid-state equipment.

32.49 ELEVATOR SPECIFICATIONS

Two basic types of specifications for elevator equipment, as for other types of equipment, are utilized. These are the prescriptive (equipment-based) and performance (outcome-based) approaches. Performance specifications describe job conditions and invite contractors to submit detailed proposals that will meet explicit design criteria. The burden of comparing proposals then falls upon the owner, who—if competent to properly perform such an evaluation—would probably do better to utilize an equipment-type specification in the first place.

In recent years, the use of performance specifications has increased because of the advent of preengineered, premanufactured systems. These are supplied by the major elevator manufacturers and have the following advantages:

1. Approximately 10% lower cost than a custom-designed system
2. A completely engineered and tested system whose performance and cost are known exactly
3. Rapid delivery
4. Minimum supervision required by the owner and architect

If architects decide to use a custom-designed system, they must prepare detailed drawings and specifications. The specifications must include:

- Elevator type, rated load, and speed
- Maximum travel
- Number of landings and openings
- Type of control and supervisory system
- Details of car and shaft doors
- Signal equipment
- Characteristics of the power supply
- Finishes

The last item can be left as a dollar allowance for architectural treatment of the car interior. Because the selection of, and technical specifications for, elevators are specialized and complex, the services of an elevator consultant are usually required.

In addition to the technical portions of the specifications, it is imperative that the following items be covered in detail.

(a) Owner's Responsibility

The general construction contractor (acting for the owner) normally provides the following:

1. The hoistway, including a properly designed, lighted, drained, waterproofed, and ventilated machine room and pit
2. Access doors, ladders, and required guards
3. Guide rail bracket supports, and support for machine and sheave beams
4. Electric feeder terminating in a switch in the machine room
5. Hoistway outlets for lighting, power, and telephone
6. Temporary lighting and power during construction
7. Concrete machine foundations
8. Vents, holes, and other work to satisfy fire codes
9. All cutting, patching, and fabricating of walls, beams, masonry, and so on
10. Coordination of all work
11. Any special work, as negotiated and specified

(b) Elevator Contractor's Responsibility

The elevator contractor shall provide a complete, working, tested, and approved system in accordance with specifications, plus any special work such as painting, special tests, work scheduling, and temporary elevator service. The system is "inserted" into the building framework described in Section 32.49(a).

(c) Special Job Conditions

These include work restrictions, scheduling, penalties or bonuses, test reports, and the like.

In alteration and modernization work, the problems of coordination are complex, and an elevator contractor experienced in this type of work should be selected. To this end, in all elevator contract work, bids should be solicited from parties named on qualified bidder lists. A complete elevator contract includes a warranty and provisions for maintenance of the installation for a specific period after completion.

32.50 INNOVATIVE EQUIPMENT

The elevator industry is constantly developing new equipment to improve the operation and safety of standard systems. In addition, novel designs that are essentially different from standard traction arrangements are always being developed in an attempt to increase the efficiency of space use and to decrease the high cost of standard traction machinery. Among the interesting designs being developed in the first category is one that permits a car to travel horizontally in addition to its normal vertical motion, the purpose of which is to increase the number of cars using a single shaft. The second category includes a design using a linear motor (as opposed to a rotating unit) to supply traction power. These and several other special designs are discussed in Chapter 33.

A recently developed interesting variation of the conventional traction design that effects a considerable space reduction is shown in Figs. 32.33–32.36. At this writing, its principal applications are in low-speed, low-rise installations now generally serviced by hydraulic elevators, but with higher speeds and rises under development. The novelty of the design lies in the use of a flat (disc-shaped), synchronous AC gearless hoisting motor, which, due to its flat disc shape, can be mounted directly on the main car guide rail at one side of the shaft (see Fig. 32.35). This essentially removes the need for a penthouse and a large machine room above the hoistway. Due to the traction motor's position

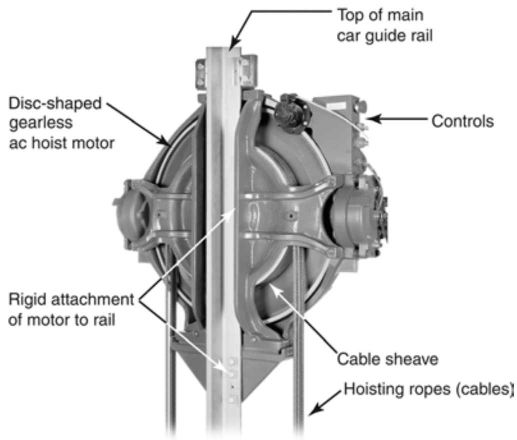


Fig. 32.33 *Disc-shaped hoisting motor rigidly mounted on the elevator guide rail. The AC synchronous motor is connected directly to the hoisting cable drive sheave with no intervening gears. Brakes and controls are built into the assembly.*

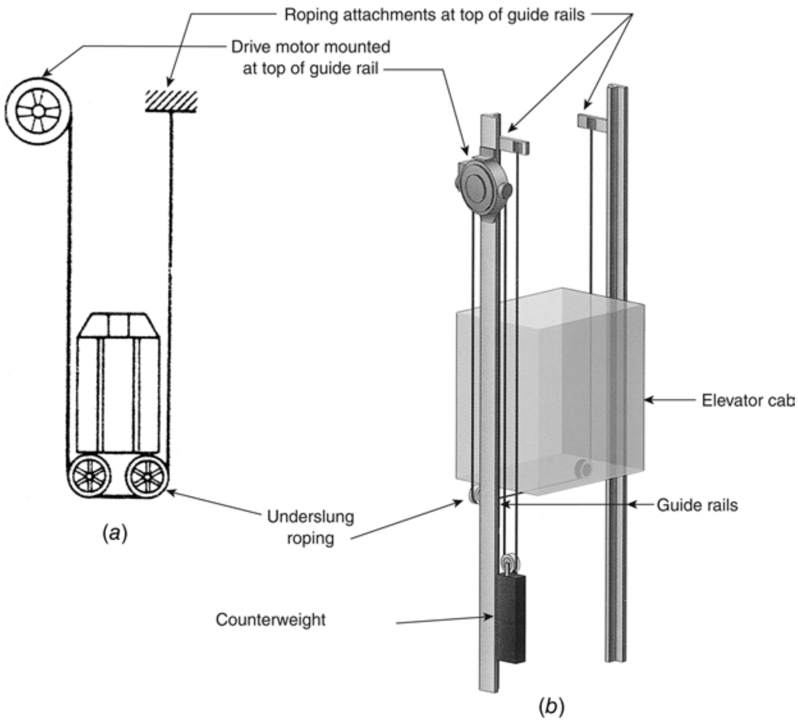
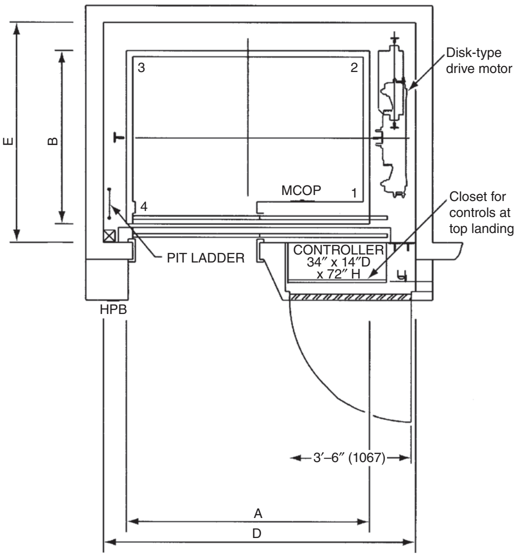


Fig. 32.34 *Schematic (a) and pictorial (b) representations of the disc-motor-driven elevator arrangement.*



(*a*)

MonoSpace Elevator System	
Speed	200 FPM (1.0 m/s)
Capacity	2500 lb. (1134 kg)
A	7'-0" (2134)
B	5'-0" (1524)
D	9'-0" (2744)
E	6'-4" (1931)
Entrance Types	Single Slide
Overhead (O)	12'-9" (3887) min
Minimum Travel	8'-4" (2540)
Maximum Travel	80'-0" (24384)
Landings Served	2 - 10
Pit (P)	5'-6" (1677) min
Machine Room (W x D x H)	3'-9" x 16" x 8'-0" (1143 x 407 x 2439)

(*b*)

Fig. 32.35 *(a) Section through the top of a hoistway showing dimensional data for a single 2500-lb (1134-kg), 200-fpm (1-m/s) installation with a rise of up to 80 ft (24 m). Note that the drive motor occupies less than 2 ft (0.6 m) in the width of the hoistway and that the elevator motion and operating controls (Section 32.4) are installed in a closet 42 in. (1.07 m) wide and approximately 20 in. (508 mm) deep at the top landing. (b) Elevator system basic data for the simplex (single) unit shown in (a). (Courtesy of Montgomery-KONE.)*

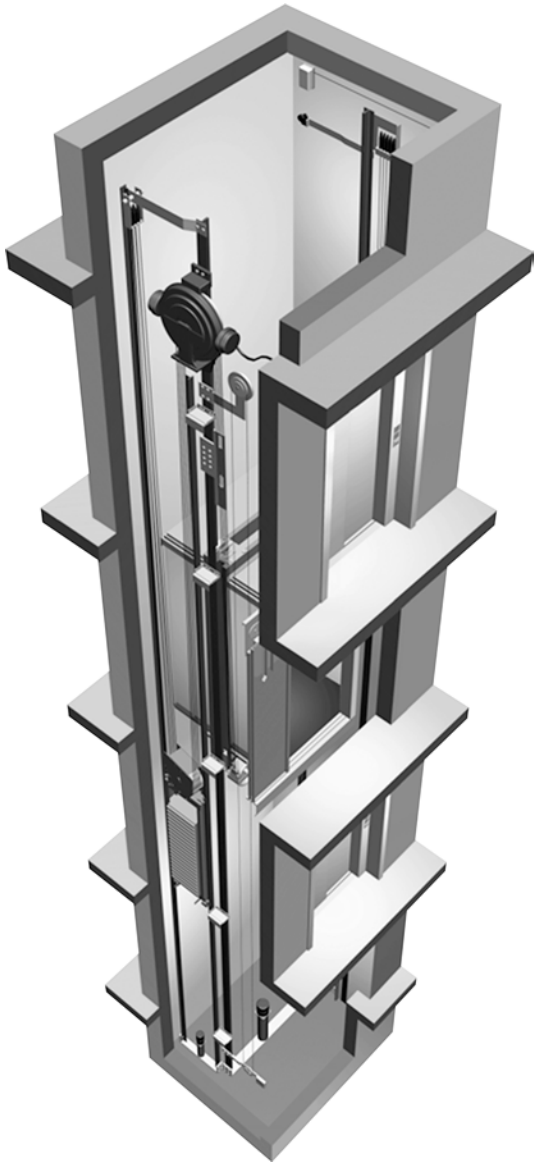


Fig. 32.36 *Pictorial representation of a disc-type traction motor hoistway showing the system's essentials.*

at the side of the hoistway, the car is roped in an underslung arrangement, as shown in Fig. 32.34. Additional space economy is achieved by the use of a small drive controller built into an alcove at the top landing (see Fig. 32.35). The pictorial hoistway representation in Fig. 32.36 shows the equipment arrangement, demonstrating the absence of a penthouse and the limited machine room space requirement. An additional advantage of this arrangement is that the elevator loads and reactions are borne by the (stiffened) guide rail and transferred directly to the concrete pit below the bottom landing. This reduces the reactions borne by the machine room level in a conventional traction design and results in reduced structural loads. Compared to hydraulic elevators, this design exhibits considerable energy economy due to its use of a gearless traction machine.

32.51 CASE STUDY—VERTICAL TRANSPORTATION

Hong Kong International Commerce Center

Project Basics

- Location: West Kowloon, Hong Kong, People's Republic of China
- Latitude: 22.3°N; longitude: 114.1°W; elevation: 60 ft (18.3 m) above sea level
- Heating degree days: 425 base 65°F (236 base 18.3°C); cooling degree days: 8284 base 50°F (4602 base 10°C); annual precipitation: 88 in. (2235 mm)
- Building type: New construction; mixed-use composed of offices, a hotel, recreation areas, retail space, and an observation deck
- Size: 2,800,000 ft^2 (260,000 m^2)
- Completed 2010

Fig. 32.37 *The ICC tower and its immediate context. (© SHK Properties; used with permission.)*

Fig. 32.38 *Lower lobby level showing entry to the lower half of the double-decker elevator cars. (© Julia Lau; used with permission.)*

(*a*) (*b*)

Fig. 32.39 *(a) Card key entry system for security. (b) Card is placed under the monitor for identification. (© Julia Lau; used with permission.)*

(*a*)

(*b*)

Fig. 32.40 *(a) Main "double" lobby showing escalators and elevator entry. (b) Entry to elevators to specific floors. (© Julia Lau; used with permission.)*

(*a*) (*b*)

Fig. 32.41 *(a) Card reader to interior elevator lobby. (b) Multiple entries for high traffic flow. (© Julia Lau; used with permission.)*

- Client: Sun Hung Kai Properties
- Design team: Kohn Pedersen Fox Associates, Wong & Ouyang Architects Ltd., and J. Roger Preston (Building Services Engineer) are key collaborators on the design development of the vertical transportation for the project.

Background. The 118-story International Commerce Center (ICC), designed by Kohn Pedersen Fox Associates (KPF), was the winning entry in an international design competition. A mixed-use building, composed of offices, a hotel, recreation areas, retail space, and an observation deck, the ICC as a whole serves an important role in the larger Union Square reclamation project. As of 2013, it is the tallest building in Hong Kong. The ICC is embedded with intelligent elevator, heating/

Fig. 32.42 *View from upper lobby to lower lobby at street level. (© SHK Properties; used with permission.)*

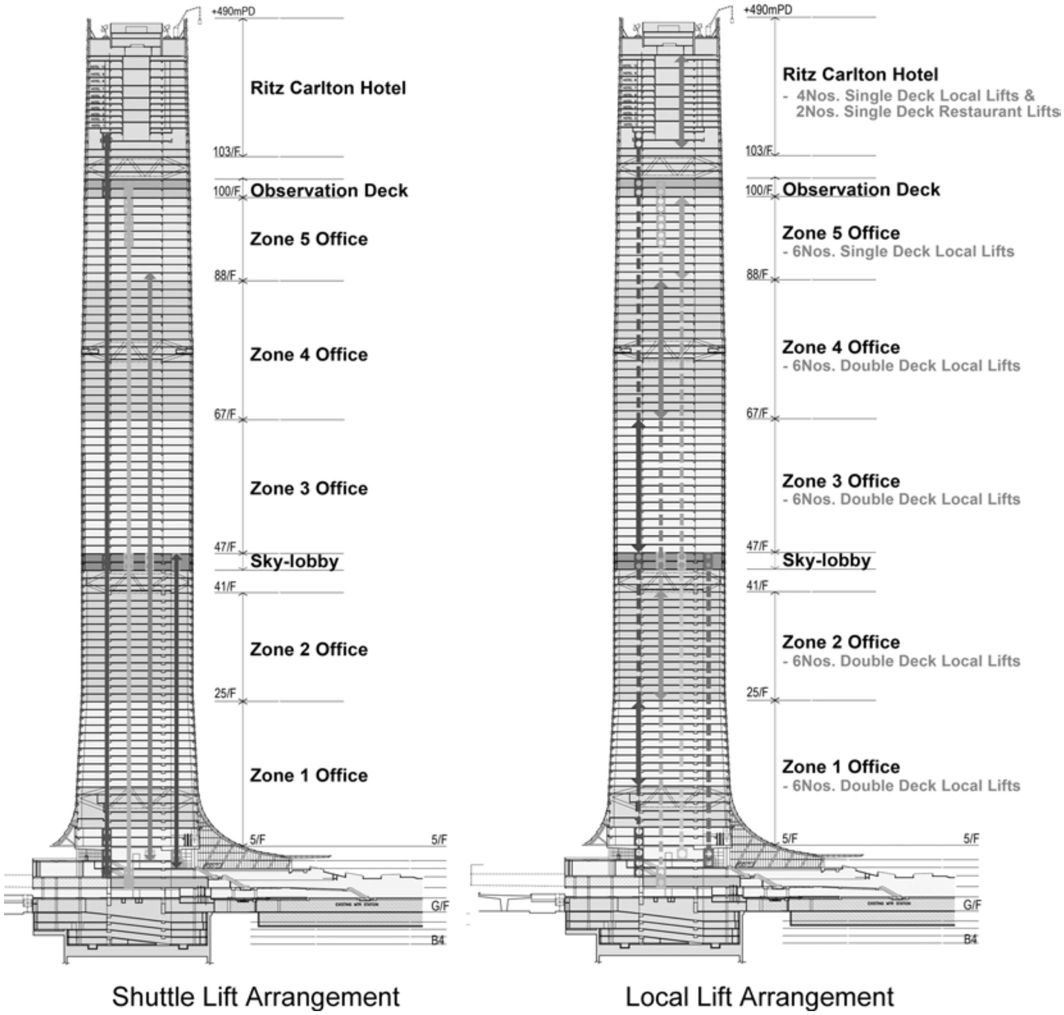


Fig. 32.43 *Shuttle lift arrangement (left) shows fast travel to specific destinations, and local lift arrangement (right) shows intermittent stops between and within zones. (© Wong & Ouyang (HK) Ltd.; used with permission.)*

cooling, and water-reclamation systems, while also being integrated into the municipal transit network. Design principles, client values, and a collaborative as well as interdisciplinary design process were important to the success of the project.

Context. The ICC was designed as an iconic structure that would support high-end finance, tourism, shopping, and hospitality. Kowloon Station, with which the ICC is closely integrated, aside from supporting eleven million passenger-journeys per day (Malott, 2011) is linked, via high-speed rail, subway, bus, and ferry terminals, to both mainland China and Hong Kong International Airport. In dealing with this programmatic juxtaposition, KPF built upon precedents such as the Met Life building over Grand Central Station and the JR Central Towers in Nagoya, Japan. Anticipating 30,000 visitors per day, the ICC pursued a multi-deck elevator system, with intelligent access controls, in order to increase the efficiency of the interior vertical transportation network, both in terms of energy expended, and time spent in the elevator.

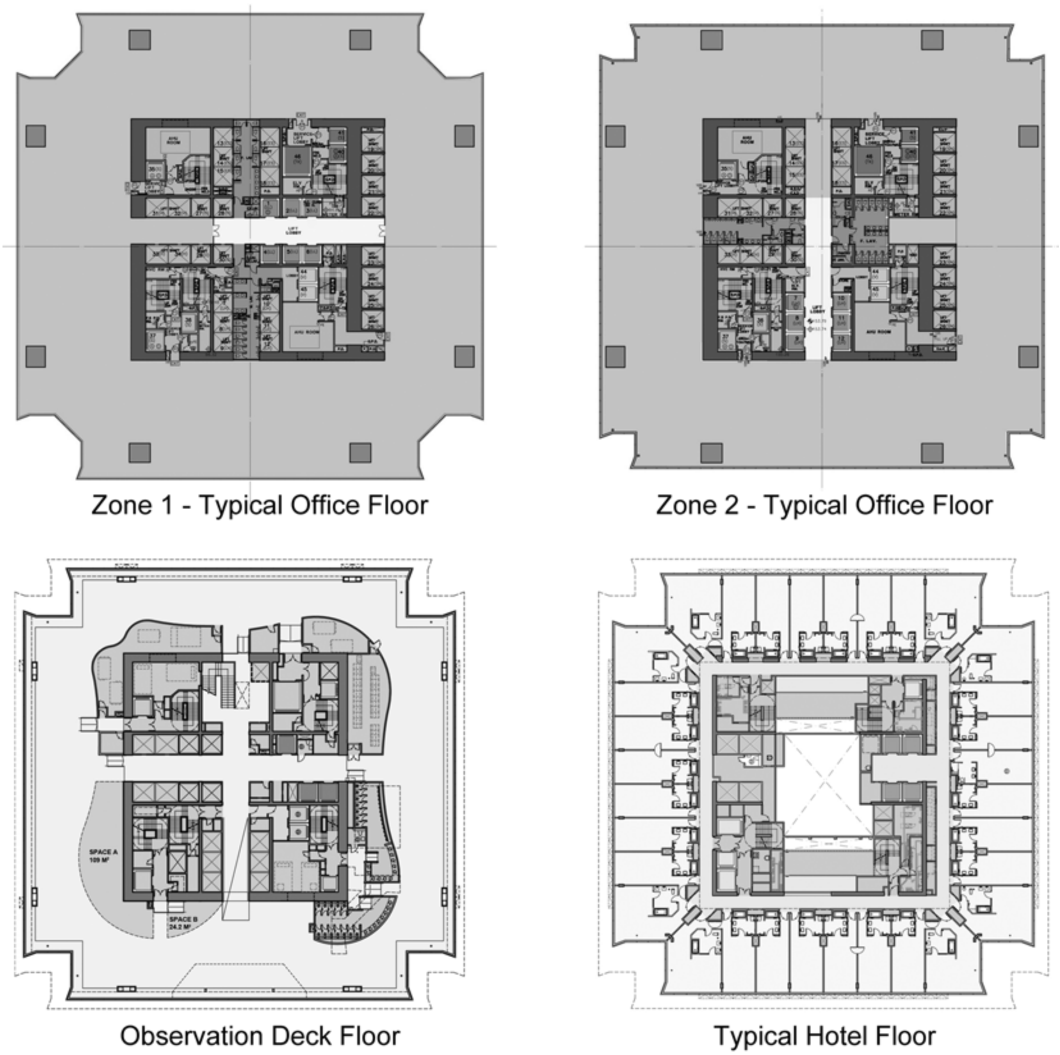


Fig. 32.44 *Typical floor arrangements for office zones, observation deck, and the hotel. (© Wong & Ouyang (HK) Ltd.; used with permission.)*

Design Intent. The design was meant to integrate high-density development, high-technology efficiency, and transit-network integration.

The leading principles behind the design were as follows:

- Set an iconic precedent for dense, integrated, and sustainable development for Hong Kong.
- Provide for the functional needs of the mixed uses that the ICC supports.
- Implement an intelligent elevator system that satisfies both the expected passenger loads and the multi-use nature of the building.
- Use intelligent HVAC systems.
- Use water reclamation/reuse systems.

The architects came up with an effective vertical transportation strategy that provides good quality lift service, and at the same time, developed floor plans that optimize space utilization for all zones of the building.

The office portion of the tower is divided into five office zones. Double-deck elevator cabs minimize the requirement for lift shafts and are employed to serve the first four zones. Zones 1 and 2 are served from the two entry levels. Zones 3 and 4 are reached via the sky-lobby. Zone 5 has an independent drop-off with direct access via single-deck elevators.

The Ritz-Carlton Hotel has its own drop-off and a distinctive hotel entrance with a magnificent view of the Victoria Harbor. Guests take the shuttle lifts to the reception area at the 103rd floor, before using local lifts to access the top-zone guestrooms. Sandwiched between the Ritz-Carlton and the office portion is Sky100 with two observation decks. The general public can take the shuttle lifts from the ticketing office in the podium below.

Design Criteria and Validation. The project was intended to serve as a novel prototype by which skyscrapers could be designed and understood. Aside from the sheer scale of the project, the nature of its mixed-use functions required KPF to approach the project in a collaborative manner. Kohn Pedersen Fox Associates, Wong & Ouyang Architects Ltd., and J. Roger Preston (Building Services Engineer), along with other specialist consultants, collaborated to achieve this end, and to help synchronize, more fully, the original design intent with the outcome.

Performance Data. Information available to date suggests success in a range of fields, but particularly in the areas of urban transportation integration, and vertical passenger movement. In terms of the latter, the ICC utilizes a wide variety of elevators, including double-deck passenger, service, emergency service, VIP, and freight elevators. This helps to move an estimated 30,000 people/day through the building in an efficient and less-energy-consuming manner. In order to optimize system performance, an intelligent identification system also helps to group passengers according to their destination requirements.

The building contains 80 Schindler elevators, 40 of which are double-deck elevator cars. They travel at speeds anywhere from 11.5 fps (3.5 m/s) to 29.5 fps (8.9 m/s), and cover distances from 236 ft (71.9 m) to 1555 ft (474 m) (Schindler Group). Such double-deck systems, optimized via intelligent transit management systems, are crucial for multi-use and super-high structures such as the ICC for satisfying the large daily inflow of visitors, while not sacrificing rentable floor space. In dealing with buildings even taller than the ICC, consultants have proposed the use of triple-deck elevator systems (Knight, 2005).

FOR FURTHER INFORMATION

Wong & Ouyang (HK) Architects Ltd.: http://www.wongouyang.com

Kohn Pedersen Fox Associates: http://www.kpf.com

Sun Hung Kai Properties: http://www.shkp.com/en-US

Knight, W. 2005. "Architects Plan Kilometre-High Skyscraper." *NewScientist*. http://www.newscientist.com/article/dn8445-architects-plan-kilometrehigh-skyscraper.html#.UfYUZKzgeS0

Schindler Elevators: http://www.schindler.com

Malott, D. 2011. "International Commerce Center," *Elevator World*, May.

Schindler Group, "East Meets West," *Next Floor*. http://www.schindler.com/content/dam/web/us/PDFs/NF-References/ICC.pdf

References and Resources

Goetz, A. 2003. *Up, Down, Across*. Merrell Publishers. London.

Stein, B., J. Reynolds, and W. McGuinness. 1986. *Mechanical and Electrical Equipment for Buildings*, 7th ed. John Wiley & Sons. New York.

Strakosch, G. R. 1983. *Vertical Transportation, Elevators and Escalators*, 2nd ed. John Wiley & Sons. New York.

Strakosch, G. R. (ed.) 1998. *The Vertical Transportation Handbook*. John Wiley & Sons. New York.

CHAPTER 33

Vertical Transportation: Special Topics

CHAPTER 32 DEALT PRIMARILY with the construction, control, and selection of passenger elevators. These elevators move in dedicated shafts with the elevator machinery usually placed near the shaft. This chapter discusses elevators with special shaft arrangements, special cars, lifting arrangements other than traction/hydraulic, and elevators designed primarily to carry freight. The chapter closes with a section devoted to materials handling and movement in buildings using elevator-like traction cars and other means.

SPECIAL SHAFT ARRANGEMENTS

The fact that each elevator in a building typically has a full-height basement-to-penthouse shaft that occupies valuable building space—and that the elevator car only uses part of the space and only for part of the time—has always disturbed finance-conscious building operators. Development of high-speed drives and very sophisticated control systems has been spurred, in part, by the desire to increase the efficiency with which elevators use building space. An alternate approach to this problem lies in innovative use of shaft space so that more than one car can use a single shaft. A detailed analysis of these solutions is beyond the scope of this chapter; however, a short review is possible.

33.1 SKY LOBBY ELEVATOR SYSTEM

For skyscraper buildings and high-rise multiple-use buildings (such as the John Hancock Center in Chicago)—which are, in effect, stacked multiple buildings—the elevator solution may involve transporting large groups of people from the street lobby to an upper lobby called a *sky lobby* or *plaza*. At this point, the passengers transfer to another elevator to continue their upward journey.

The traditional approach in tall, single-purpose buildings is to vertically zone the structure and to provide banks of elevators that serve groups of floors. The difficulty with this solution is that the upper-zone cars travel through a long, expensive blind shaft to reach the floors being served. The sky plaza approach stacks (figuratively) two (or more) shafts vertically, with a lobby in between. The result is to have *two* cars operating in the equivalent of a single full-height shaft. To mitigate the annoyance felt by passengers taking a lengthened (interrupted) trip, the sky lobby is attractively appointed and may serve as an observation floor. Also, an elevator trip broken up by a lobby stop is thought to be less annoying than a somewhat shorter but still long, uninterrupted one. Finally, this plan is used principally where a clear differentiation in building use occurs, usually consisting of office areas below and residential units above, as in the John Hancock building. Thus, most lower-section occupants never use the sky lobby. Passengers headed for upper zones can use a sky lobby "shuttle" that travels from the entry level to the sky lobby and then continue the trip in an upper-section car.

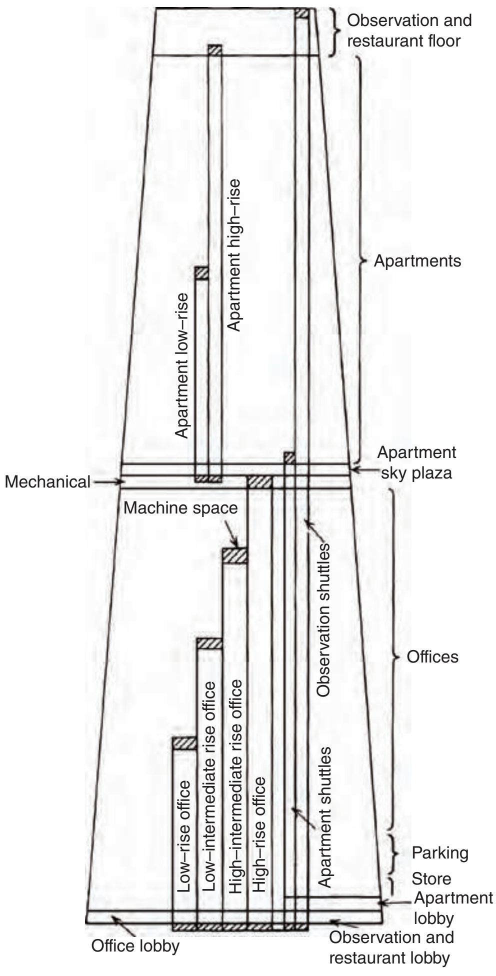


Fig. 33.1 *The use of a sky plaza in this dual-purpose building (the John Hancock Center, Chicago) eliminates the blind shafts below the upper-section (residential) elevators. The lengthened trip time is well tolerated by riders destined for the upper residential section, whereas the lower office section remains unaffected and retains its short interval and trip time. (G. R. Strakosch,* Vertical Transportation*, 2nd ed. John Wiley & Sons; reprinted with permission.)*

Some designs also provide for a single-shaft upper-zone elevator group that serves upper-zone passengers who prefer not to use the sky lobby. A schematic drawing of the elevator arrangement in the John Hancock building should suggest the spatial advantages of the system (Fig. 33.1).

33.2 DOUBLE-DECK ELEVATORS

The double-deck elevator is a recently revived and revised technique to answer the needs of tall buildings such as the Willis Tower (formerly known as the Sears Tower) in Chicago and Citicorp Tower in New York City. Its principal purpose is to limit the otherwise prohibitively large amount of space occupied by elevator shafts (Fig. 33.2). The double-deck car increases shaft capacity, decreases the number of local stops, and increases the available rental area. This technique can also be combined with sky lobbies for further space economy, as was done in the Willis Tower.

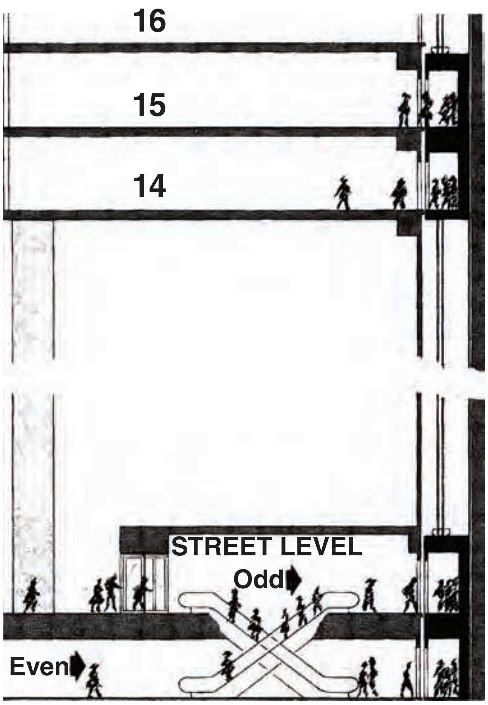
FREIGHT ELEVATORS

33.3 GENERAL INFORMATION

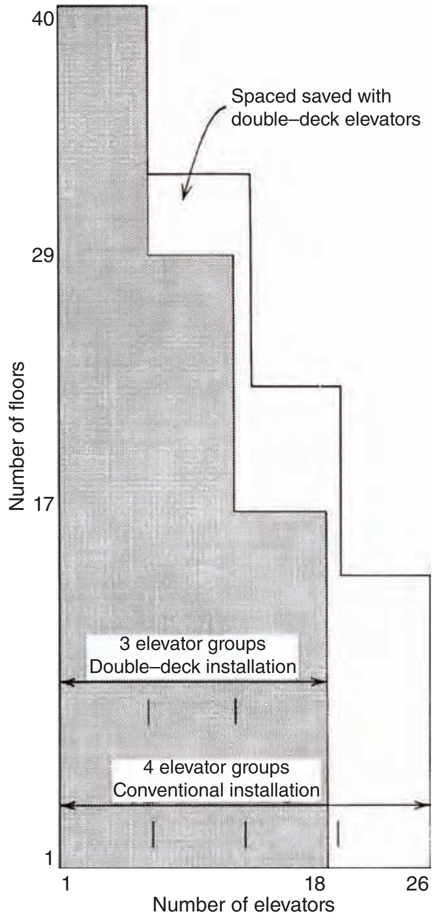
The design problem with respect to freight elevators is similar to that for passenger elevators: to transport a given load (in this case freight) efficiently, economically, and quickly. A "service" car in a building can be used as a freight elevator, but, if utilized for passenger duty at all, it must meet passenger service requirements. If passenger duty is not required or if substantial freight is to be handled, a car designed specifically for freight should be used.

Factors to be considered in freight elevator selection, in addition to tonnage movement per hour, are size of load, method of loading, travel, type of load, type of doors, and speed and capacity of cars. Due to the interrelation of these factors, the selection process involves making assumptions on the basis of recommendations and then arriving at a solution, as is done for passenger elevators.

A detailed discussion of the selection of materials-handling elevators is beyond the scope of this book because of the large number of



(a)



(b)

Fig. 33.2 *(a) A double-deck car increases car capacity and decreases shaft space demands. Coincidence of calls in the upper and lower cars reduces the number of local stops made by the double-deck unit. (b) Graphical representation of the space saved in a 40-story building by the use of double-deck elevators. (Courtesy of Otis Elevator Co.)*

considerations involved. Therefore, the following sections are restricted to descriptive material and recommendations. Inasmuch as freight elevators form such an important link in industrial processes, a careful and detailed material-flow study should be made before freight elevators are selected. Elevator manufacturers' representatives and materials-handling consultants can be very helpful in this regard.

33.4 FREIGHT CAR CAPACITY

Figure 33.3 is a section through a typical traction-type freight car shaft. Capacities corresponding to a specific platform size are due to the varying unit-area loads that are permissible. This is taken into account by the American Society of Mechanical Engineers (ASME) Standard A17.1, which has established five load classifications for freight elevators:

Class A. General Freight Loading by hand truck. Single items may not exceed 25% of the car-rated load. The rated load is based on 50 pounds per square foot (psf) (244 kg/m^2) of net inside platform area.

Class B. Motor Vehicle Loading. The elevator car will carry automobiles or automobile trucks. The rating is based on a load of 30 psf (146 kg/m^2) of net inside platform area.

Class C1. Industrial truck loading; truck carried.

Class C2. Industrial truck loading; truck not carried.

Class C3. Concentrated loading; no truck used; increments greater than 25% of rated capacity.

For classes C1, C2, and C3, the rated load is based on 50 psf (244 kg/m^2). Elevator cars have automatic leveling.

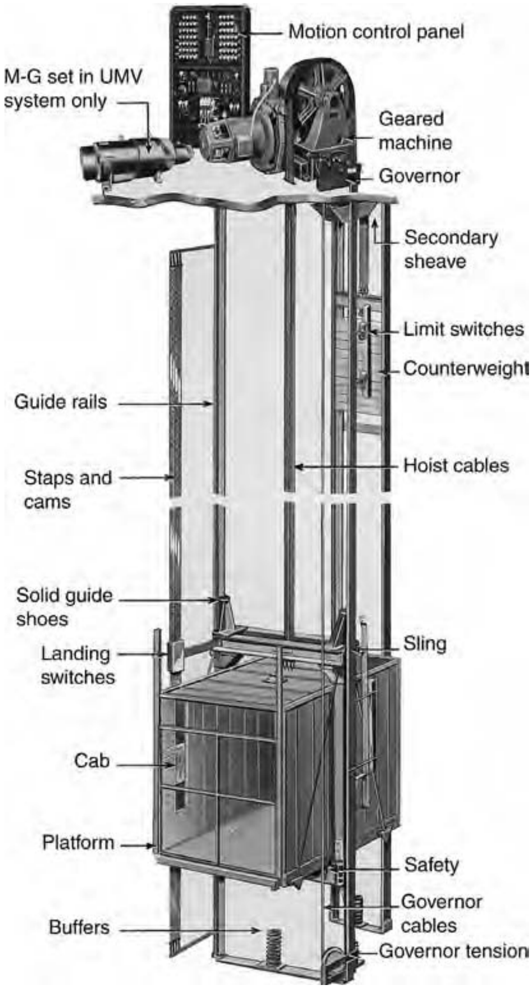


Fig. 33.3 *Components of a typical freight elevator installation utilizing a variable-voltage-controlled, geared traction machine. The sling that lifts the car is frequently arranged with double sheaves over which the hoisting ropes pass. This roping arrangement increases the mechanical advantage of the lifting ropes.*

33.5 FREIGHT ELEVATOR DESCRIPTION

As speeds are generally between 50 and 200 fpm (0.25 to 1.0 m/s), a geared-type traction machine or a hydraulic unit is used. The preferred system of control is collective, with a variable-voltage DC supply, either unit multivoltage (UMV) or variable-voltage, variable-frequency (VVVF). A two-speed AC rheostatic control may be used if the car is used infrequently (fewer than five trips a day), economy is very important, accurate leveling is not essential, and a rougher ride is tolerable.

For low-rise installations, a hydraulic unit is most often employed. These, like the variable-voltage DC traction units, provide accurate control, smooth operation, and accurate automatic leveling. Hydraulic units rarely exceed 60 ft (18 m) in height and operate at speeds of up to 125 fpm (0.64 m/s). Accessories such as governors, safeties, and brakes are similar to those for passenger elevators previously described.

General-purpose freight elevators, whether traction (Fig. 33.4) or hydraulic (Fig. 33.5), in load ranges of up to 20,000 lb (9072 kg), are standard design items applicable to all types of commercial and industrial buildings. Heavier units are individually engineered. Units of 20,000 lb (9072 kg) and more require special safeties. As with passenger elevators, structural reactions for traction units are supplied by the manufacturer to the architect, who is responsible for providing adequate structural supports. This item is of great importance in larger car installations, because traction unit rails must be supported every few feet, and additional steel must be provided to accomplish this.

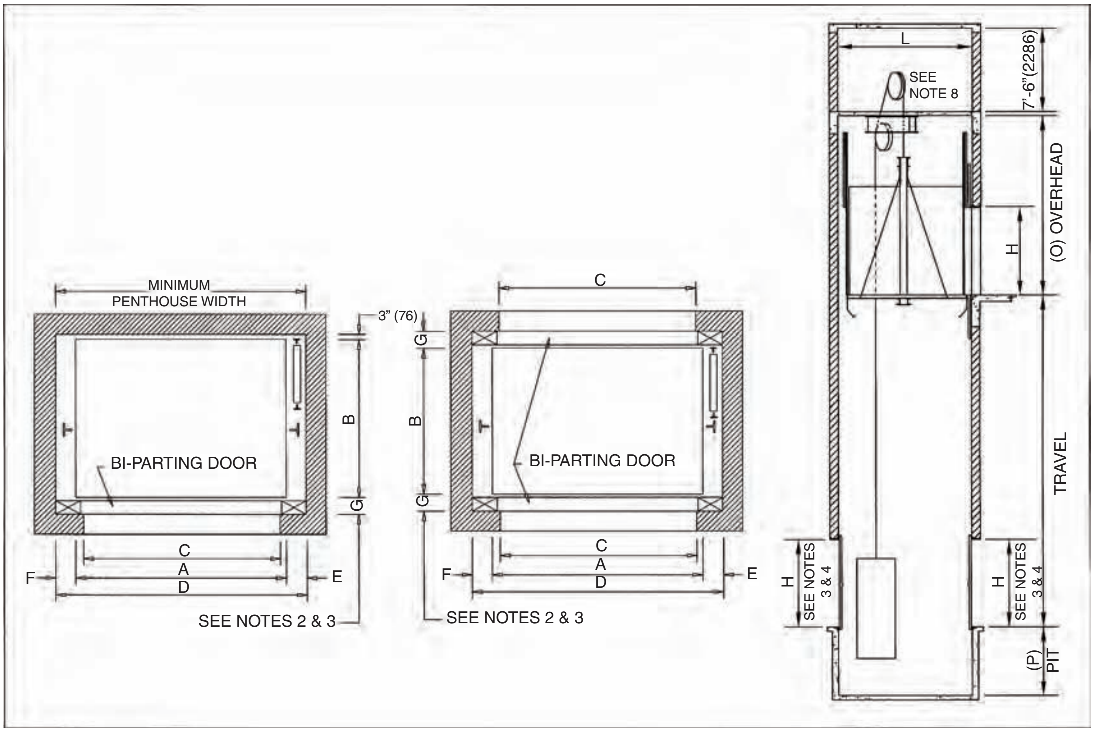
33.6 FREIGHT ELEVATOR CARS, GATES, AND DOORS

Cars for freight service are normally built of heavy-gauge steel with a multilayer wooden floor, the entire unit being designed for hard service. Guarded ceiling light fixtures are required. Car gates slide vertically and are a minimum of 6 ft (1.8 m) high. Hoistway doors are normally vertical lift, center-opening, manual or power-operated. Both car gate and hoistway doors are counterweighted and open fully to give complete floor and head clearance.

33.7 FREIGHT ELEVATOR COST DATA

The cost of a freight elevator installation, as with passenger elevator installations, is dependent upon many factors, principally capacity, type of control, use, and type of door operation.

Exact pricing, like specific selection, is outside the scope of this discussion. A reputable



LIGHT AND MEDIUM DUTY FREIGHT ELEVATORS					
CAPACITY	2500 lbs. (1134 kg)	3000 lbs. (1361 kg)	4000 lbs. (1814 kg)	6000 lbs. (2722 kg)	8000 lbs. (3629 kg)
A	5'-4" (1626)	6'-4" (1930)	6'-4" (1930)	8'-4" (2540)	8'-4" (2540)
B	7'-0" (2134)	8'-0" (2438)	8'-0" (2438)	10'-0" (3048)	10'-0" (3048)
C	5'-0" (1524)	6'-0" (1829)	6'-0" (1829)	8'-0" (2438)	8'-0" (2438)
D	7'-10"(2388)	8'-10"(2692)	8'-10"(2692)	10'-10"(3302)	10'-10"(3302)
E	1'-7" (483)	1'-7" (483)	1'-7" (483)	1'-7" (483)	1'-7" (483)
F	0'-11" (279)	0'-11" (279)	0'-11" (279)	0'-11" (279)	0'-11" (279)
L	13'-0" (3962)	14'-0" (4267)	14'-0" (4267)	14'-0" (4267)	14'-0" (4267)

HEAVY DUTY POWER TRUCK LOADING FREIGHT ELEVATORS					
CAPACITY	10,000 lbs. (4536 kg)	12,000 lbs. (5443 kg)	16,000 lbs. (7258 kg)	18,000 lbs. (8165 kg)	20,000 lbs. (9072 kg)
A	8'-4" (2540)	10'-4" (3150)	10'-4" (3150)	10'-4" (3150)	12'-4" (3759)
B	12'-0" (3658)	14'-0" (4267)	14'-0" (4267)	16'-0" (4877)	20'-4" (6198)
C	8'-0" (2438)	10'-0" (3048)	10'-0" (3048)	10'-0" (3048)	12'-0" (3658)
*D	11'-4" (3454)	13'-6" (4115)	14'-0" (4267)	14'-2" (4318)	16'-6" (5029)
E	1'-7" (483)	1'-7" (483)	1'-7" (483)	1'-7" (483)	1'-7" (483)
F	0'-11" (279)	0'-11" (279)	0'-11" (279)	0'-11" (279)	0'-11" (279)
L	14'-0" (4267)	15'-0" (4572)	15'-0" (4572)	17'-0" (5182)	21'-0" (6400)

MINIMUM OVERHEAD & PIT DIMENSIONS FOR LIGHT & MEDIUM DUTY FREIGHT ELEVATORS				
SPEED	50 FPM (0.25 m/s)	75 FPM (0.38 m/s)	100 FPM (0.51 m/s)	200 FPM (1.02 m/s)
O	16'-0"(4877)	16'-0" (4877)	16'-0"(4877)	16'-0"(4877)
P	5'-6"(1676)	5'-6" (1676)	5'-6"(1676)	6'-0"(1829)

NOTES:

2. Dimension G = 5" (127) for regular type counterbalanced hoistway doors and 6 3/4" (172) for pass type counterbalanced hoistway doors.
3. Pass type hoistway doors are required when floor heights are less than 11'-0" (3353) for 7'-0" (2134) openings and less than 12'-6" (3810) for 8'-0" (2438) openings.
4. Dimension H = 7'-0" (2134) on light and medium duty and 8'-0" (2438) (or as required) for heavy-duty doors. Doors higher than 8'-0" (2438) require additional overhead.
8. 2:1 Roping recommended for heavy duty power truck loading freight elevators

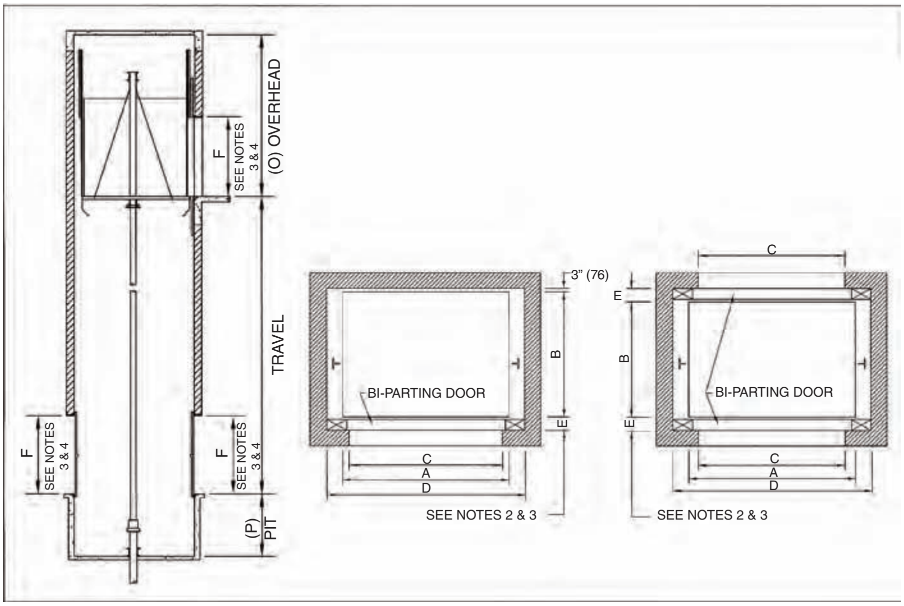
* D dimension includes space required when vertical columns are added (inside hoistway) for rail support. If no columns required, D=A+E+F.

Fig. 33.4 *Typical dimensional data for traction-type freight elevators. (Courtesy of Montgomery-KONE.)*

manufacturer or elevator consultant should be sought for such information. Some general remarks on pricing, however, follow:

1. Variable-voltage-controlled equipment, depending on the type, costs 20% to 50% more than rheostatically controlled equipment.
2. Above a basic two-floor rise, the cost increases linearly with rise.
3. Electric door operation can increase the cost of a car installation 10% to 25%.

As an example of *comparative* pricing, using a nominal 100 monetary units for an 8000-lb (3630-kg), 75-fpm (0.38-m/s), four-floor, manual-door car with AC rheostatic control and automatic leveling, the same car with variable-voltage control, 150 fpm (0.76 m/s), and electrically operated doors would cost approximately 180.



LIGHT AND MEDIUM DUTY FREIGHT ELEVATORS						
CAPACITY	2000 lbs. (907 kg)	3000 lbs. (1361 kg)	4000 lbs. (1814 kg)	5000 lbs. (2268 kg)	6000 lbs. (2722kg)	8000 lbs. (3629 kg)
A	5'-0" (1524)	5'-6" (1676)	6'-6" (1981)	8'-6" (2591)	8'-6" (2591)	8'-6" (2591)
B	6'-0" (1829)	7'-0" (2134)	8'-0" (2438)	10'-0" (3048)	12'-0" (3658)	12'-0" (3658)
C	4'-8" (1422)	5'-2" (1575)	6'-2" (1880)	8'-2" (2490)	8'-2" (2490)	8'-2" (2490)
D: **manual doors**	6'-4" (1930)	6'-10" (2083)	7'-10" (2388)	9'-10" (2997)	10'-0" (3048)	10'-6" (3200)
D: **power doors**	6'-10" (2083)	7'-4" (2235)	8'-4" (2540)	10'-4" (3150)	10'-6" (3200)	10'-6" (3200)
O: 7'-0" door ht. (2134)	13'-2" (4013)	13'-2" (4013)	13'-2" (4013)	13'-2" (4013)	13'-2" (4013)	13'-2" (4013)
P: 7'-0" door ht. (2134)	4'-0" (1219)	4'-0" (1219)	4'-0" (1219)	4'-6" (1372)	4'-6" (1372)	5'-0" (1524)

HEAVY DUTY POWER TRUCK LOADING FREIGHT ELEVATORS					
CAPACITY	10,000 lbs. (4536 kg)	12,000 lbs. (5443 kg)	16,000 lbs. (7258 kg)	18,000 lbs. (8165 kg)	20,000 lbs. (9072 kg)
A	10'-6" (3200)	10'-6" (3200)	10'-6" (3200)	10'-6" (3200)	12'-6" (3810)
B	14'-0" (4267)	14'-0" (4267)	16'-0" (4877)	16'-0" (4877)	20'-0" (6096)
C	10'-2" (3098)	10'-2" (3098)	10'-2" (3098)	10'-2" (3098)	12'-2" (3708)
D: **manual doors**	12'-6" (3810)	12'-6" (3810)	12'-6" (3810)	12'-6" (3810)	14'-6" (4420)
D: **power doors**	12'-6" (3810)	12'-6" (3810)	12'-6" (3810)	12'-6" (3810)	14'-6" (4420)
O: 7'-0" door ht. (2134)	13'-2" (4013)	13'-2" (4013)	13'-2" (4013)	13'-2" (4013)	13'-2" (4013)
O: 8'-0" door ht. (2438)	14'-2" (4318)	14'-2" (4318)	14'-2" (4318)	14'-2" (4318)	14'-2" (4318)
P: 7'-0" door ht. (2134)	5'-0" (1524)	6'-0" (1829)	6'-0" (1829)	6'-0" (1829)	6'-0" (1829)
P: 8'-0" door ht. (2438)	5'-0" (1524)	6'-0" (1829)	6'-0" (1829)	6'-0" (1829)	6'-0" (1829)

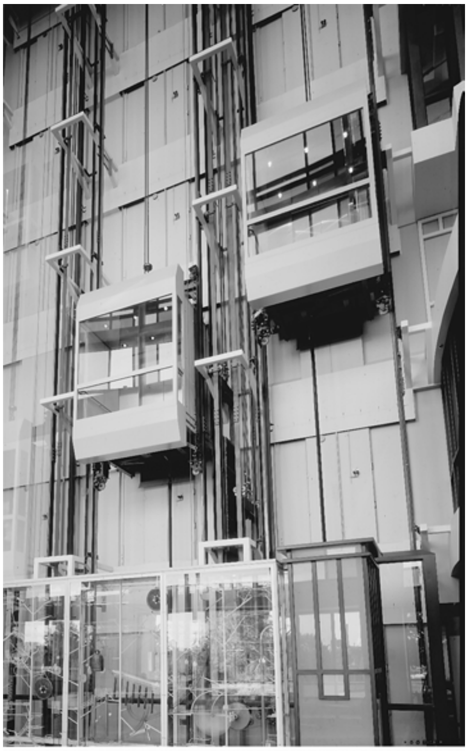
NOTES:
2. Dimension E = 5" (127) for regular type counterbalanced hoistway doors and 6¾" (172) for pass type counterbalanced hoistway doors.
3. Pass type hoistway doors are required when floor heights are less than 11'-0" (3353) for 7'-0" (2134) openings and less than 12'-6" (3810) for 8'-0" (2438) openings.
4. Layout and dimensions shown for freight elevators based on bi-parting counterbalanced type hoistway doors – dimension F.
5. Dimensions O and P are minimums based on car speeds up to 150 FPM (0.76 m/s).

Fig. 33.5 *Typical dimensional data for hydraulic freight elevators. (Courtesy of Montgomery-KONE.)*

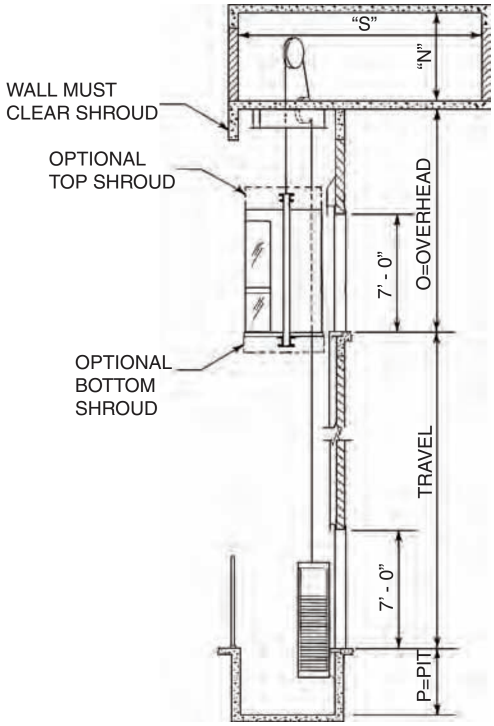
SPECIAL ELEVATOR DESIGNS

33.8 OBSERVATION CARS

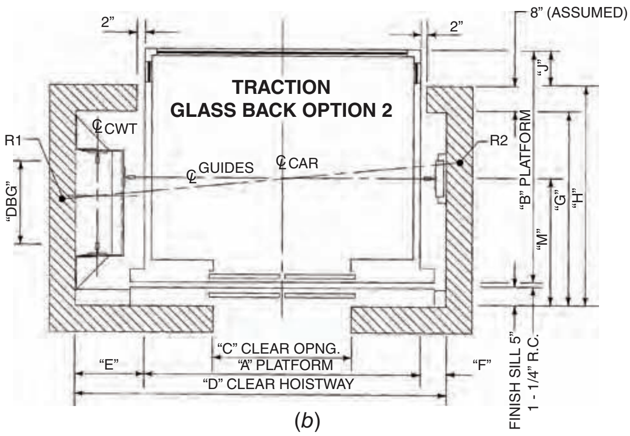
By placing the traction lifting mechanism *behind* the car, attaching the car at the back, and using a glass-enclosed, observation-style car, a spectacular unit can be constructed that becomes an attraction in itself. Basic construction and examples are seen in Figs. 33.6, 33.7, and 33.8. If the back screen is treated properly, the car gives the impression of movement with no apparent motive force or machinery.



(a)



(c)



(b)

Notes (Hydraulic and Traction)

State and local code requirements may vary. Data is for general application.

All layout details are based upon the use of center opening type entrances.

Elevator machine room temperature should be maintained between 65°F and 100°F.

Please consult Montgomery KONE for exact information for working drawings and for designs which may vary from those depicted.

(d)

Fig. 33.6 *Details of a geared, traction-type observation elevator. (a) The glass-enclosed observation portion of this elevator faces the rear. The shaftway doors are seen in the wall behind the elevator. The traction ropes are also clearly seen above each elevator. (b) Plan drawing of the unit. Note that the counterweight is mounted at the side of the car so as to be essentially invisible and not detract from the relatively uncluttered view of the car in motion. (c) Vertical section of the installation, including the overhead machine room. (d) Notes applicable to drawings (b) and (c). (Courtesy of Montgomery-KONE.)*

BASIC DIMENSIONS: TRACTION OBSERVATION ELEVATORS						
DIMENSION	CAPACITY					
	3000 lbs.		3500 lbs.		4500 lbs.	
	Option 2		Option 2		Option 2	
"DBG"	25"		31"		37"	
A	7' - 0"		7' - 0"		7' - 0"	
B	5' - 8"		6' - 6"		7' - 6"	
C	3' - 6"		3' - 6"		3' - 6"	
D	9' - 5"		9' - 5"		9' - 5"	
E	1' - 8"		1' - 8"		1' - 8"	
F	9"		9"		9"	
G	4' - 7½"		5' - 1½"		5' - 7½"	
H	5' - 3½"		5' - 9½		6' - 3½"	
J	10¾"		1' - 2¾"		1' - 8¾"	
K	NA		NA		NA	
L	NA		NA		NA	
M	3' - 4½"		3' - 10½"		4' - 4½"	
N	7' - 6"		7' - 6"		7' - 6"	
S	13' - 8"		13' - 8"		13' - 8"	
SPEED	200 fpm	350 fpm	200 fpm	350 fpm	200 fpm	350 fpm
*O(1)	14' - 8"	15' - 4"	14' - 8"	15' - 4"	15' - 2"	15' - 6"
**O(1)	15' - 2"	15' - 10"	15' - 2"	15' - 10"	15' - 2"	15' - 6"
*P	5' - 0"	5' - 6"	5' - 0"	5' - 6"	5' - 4"	5' - 10"
**P	5' - 4"	5' - 10"	5' - 4"	5' - 10"	5' - 4"	5' - 10"

NOTE: * Dimension when no shroud is used.
** Dimension when 2' - 0" shroud is used.
(1) Based on standard height cab (8' - 0" to underside of canopy).
→ The relationships between dimensions G, H, J and K are based on an assumed thickness of 8" for the rear wall of the hoistway.
→ The hoistway dimensions shown are based on a counterweight not requiring safeties.

(*a*)

VERTICAL REACTIONS	TRACTION ELEVATOR CAPACITY			
	2500 lbs.	3000 lbs.	3500 lbs.	4500 lbs.
R1	17500 lbs.	18900 lbs	20900 lbs.	24400 lbs.
R2	13900 lbs.	15000 lbs.	16300 lbs.	19100 lbs.

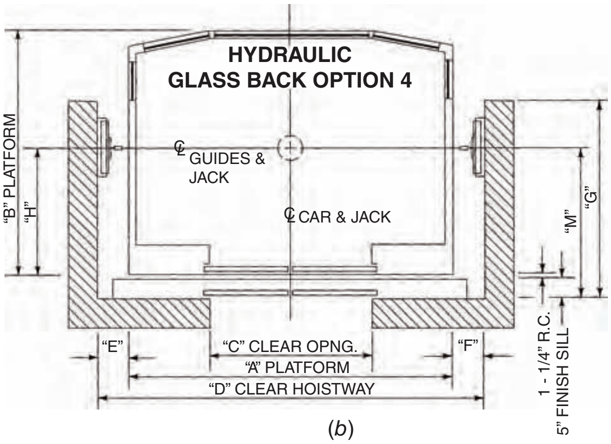
NOTE: Reactions include allowance for impact but DO NOT include weight of concrete slab. Reactions are for preliminary use only. Exact reactions will be provided when exact conditions are known.

(*b*)

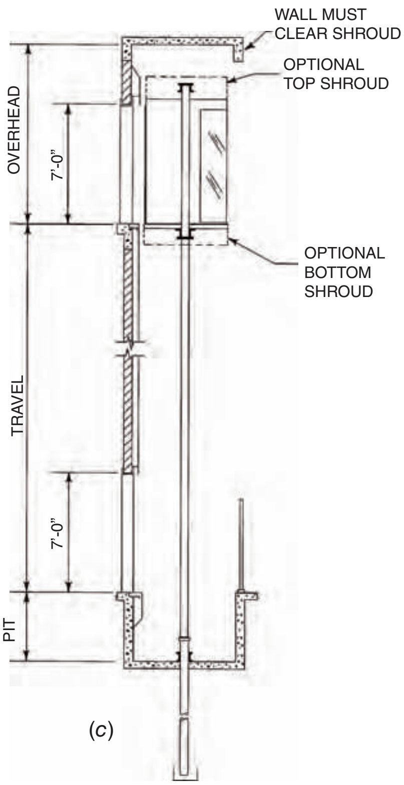
Fig. 33.7 *(a) Dimensions applicable to drawings (b) and (c) in Fig. 33.6. (b) Vertical reactions required for structural design of the elevator in Fig. 33.6. (Courtesy of Montgomery-KONE.)*

The same effect can be accomplished by using a single-jack hydraulic lift mechanism and a cantilevered car, as suggested in Fig. 33.8. Observation cars, which are placed on the *outside* of a wall, do not require shaft space. Thus, in addition to an interesting and attractive appearance, they increase the amount of usable interior space, thereby effecting a considerable cost economy.

(*a*)



(*b*)



(*c*)

BASIC DIMENSIONS: HYDRAULIC OBSERVATION ELEVATORS				
	CAPACITY			
Dimension	2500 lbs.	3000 lbs.	3500 lbs.	
	OPTION 1,2,3,4	OPTION 1,2,3,4	OPTION 1,2,3,4	OPTION 5
A	7' - 0"	7' - 0"	7' - 0"	7' - 0"
B	5' - 3"	5' - 11"	6' - 6"	7' - 2"
C	3' - 6"	3' - 6"	3' - 6"	3' - 6"
D	8' - 4"	8' - 4"	8' - 4"	8' - 4"
E	8"	8"	8"	8"
F	8"	8"	8"	8"
G	4' - 3"	4' - 7"	4' - 10 1/2"	4' - 10 1/2"
H	2' - 8 3/4"	3' - 0 3/4"	3' - 4 1/4"	3' - 4 1/4"
M	3' - 3"	3' - 7"	3' - 10 1/2"	3' - 10 1/2"

Basic dimensions outlined above are based upon conventional inground jack application.

(*d*)

HYDRAULIC MACHINE ROOM SIZES (Typically recommended)		
SIZE	CAPACITY	
	2500 lbs. & 3000 lbs.	3500lbs.
WIDTH	9' - 0"	9' - 6"
LENGTH	6' - 8"	6' - 9"
DOOR	3' - 6" × 7' - 0"	

NOTE: Hydraulic machine room location should be at the lowest landing adjacent to the hoistway. Consult your Montgomery KONE Professional for alternative locations and optimum sizes. Material above is typical for 150 FPM speed.

(*e*)

Fig. 33.8 *Hydraulic observation elevator. (a) The hydraulic plunger is clearly visible below each car against the background of the shaftway doors. (b) Dimensioned sectional drawing of the car and its enclosure. (c) Vertical section of the elevator travel. (d) Dimensions applicable to drawings (b) and (c). (e) Dimensional data for the required machine room. Note that in drawing (c), the machine room is not shown because it can be remote from the elevators, connected only by piping. (Courtesy of Montgomery-KONE.)*

33.9 INCLINED ELEVATORS

Although elevators are normally conceived as traveling vertically, this is not necessarily so. Slanted or inclined elevators have been constructed in numerous locations where a building is built onto an inclined surface, usually a hillside or mountainside. One such elevator application is shown in Fig. 33.9. The motive mechanism used varies with the angle of inclination. In most instances, the car rides on inclined rails and is pulled up by a traction cable. It is counterweighted either by a weight riding on another set of rails in the case of a single car, or by the weight of another car in a two-car installation.

33.10 AERIAL TRAMS

An aerial tram is a type of lift or cable car, typically with one or two fixed cables in an arrangement whereby one loop of the cable (haulage rope) grips the wheel that rolls on the two fixed cables. Two passenger cabins move as an electric motor drives the haulage rope to propel the aerial tramway.

In Fig. 33.10, the Portland Aerial Tram uses track cables to hoist a passenger car that carries commuters uphill 500 ft (150 m) to the Oregon Health & Science University, from Portland's waterfront district 3300 ft (1000 m) away. Two trams, each carrying up to 79 people, run using an electric motor at the bottom, which in turn pulls one car down, to pull the other car up, with the cars passing each other along the cable span.

Fig. 33.10 *The Portland Aerial Tram car takes about 3 minutes each way, connecting employees, parking, transportation, housing, and health care on the waterfront to the university hospital on the hill. (© Alison Kwok: all rights reserved.)*

Fig. 33.9 *The St. Louis Gateway Arch has a 10-passenger inclined elevator in each leg. Placement of doors, arrangement of the counterweight, and size of the shaft all depend upon the angle of incline. The car moves 82 ft (25 m) horizontally during its 386 ft (118 m) of total travel at an incline of approximately 12°. (Photo courtesy of Bethlehem Steel Corporation, which supplied the elevator rope for this installation.)*

33.11 RACK AND PINION ELEVATORS

These operate on the straightforward principle of a rotating cogged-wheel pinion attached to a vertical rack. Rotation of the pinion forces the attached car up and down along the rack (see Fig. 33.11). The advantages of this system are its inherent simplicity and safety, unlimited rise, and low maintenance and operating costs, plus minimum space requirements. The last characteristic was primarily responsible for the selection of a rack and pinion design for the 210-ft-rise (64-m) emergency elevator installed as part of the renovation and rehabilitation of the Statue of Liberty in 1986.

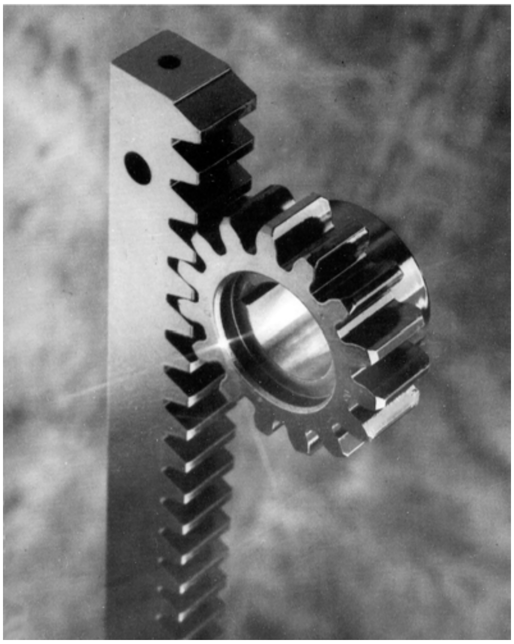


Fig. 33.11 *The basis of the rack and pinion drive is simply a driven pinion on a stationary rack; rotation of the pinion forces the structure attached to the pinion to move along the rack. (Courtesy of Alimak Elevator Co.)*

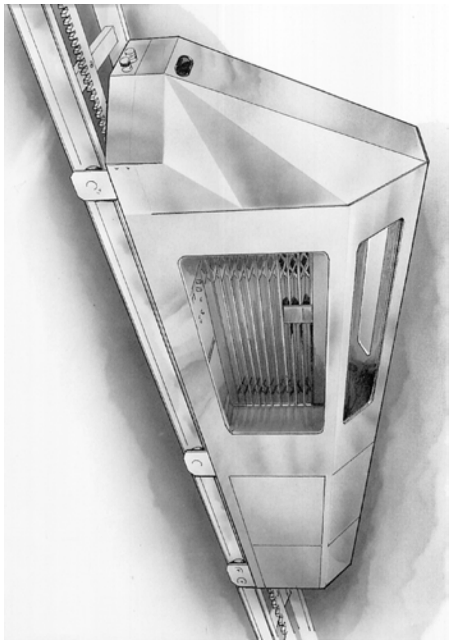


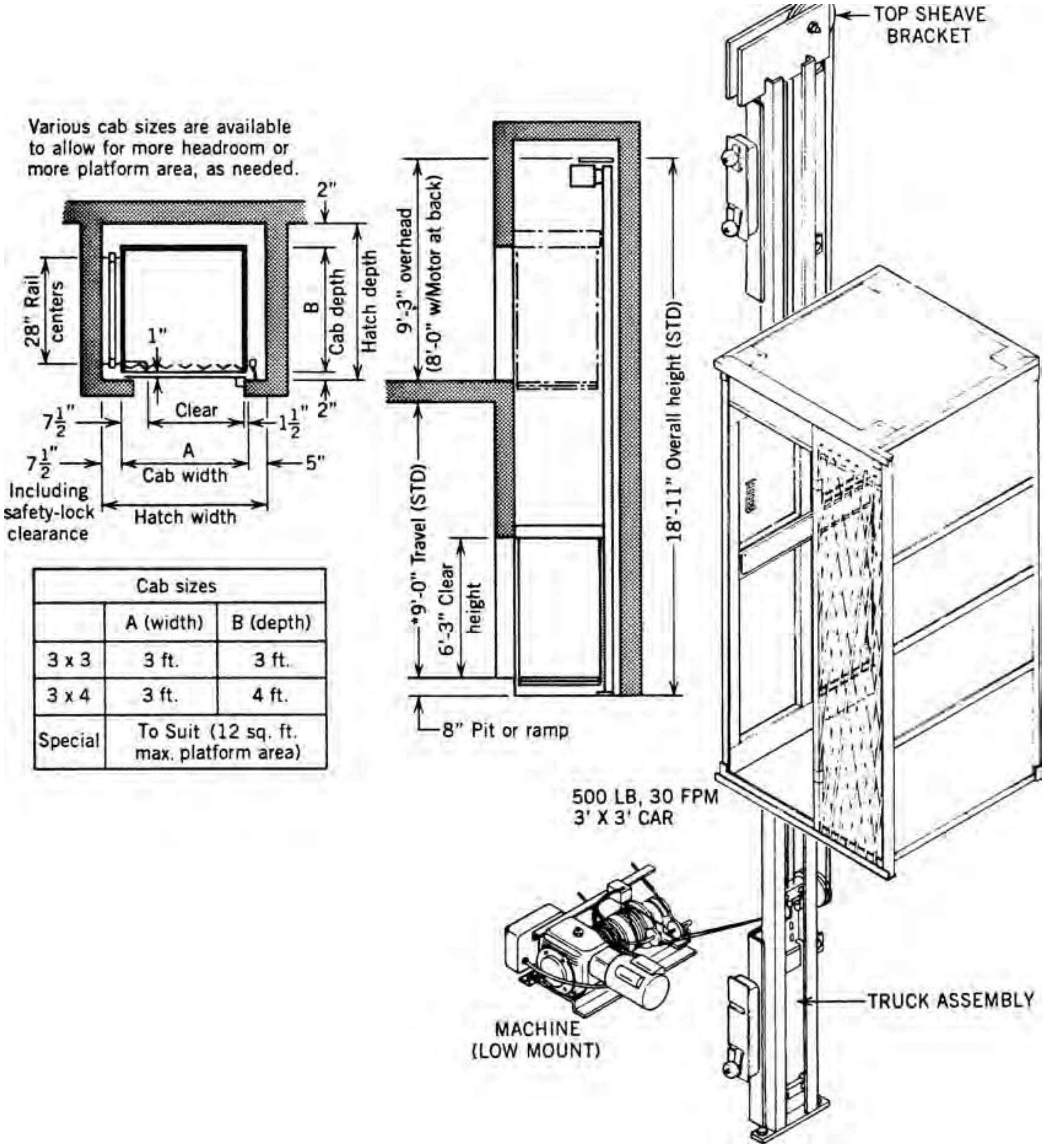
Fig. 33.12 *The rack and pinion principle is used in the very small Statue of Liberty emergency elevator. The rack extends the entire length of the shaft, and the car moves along the rack, driven by two motorized pinions below the passenger compartment. (Courtesy of Alimak Elevator Co.)*

The Statue of Liberty elevator is used primarily to evacuate victims of heart attacks. Carrying them down the 171-step spiral staircase that connects the main upper landing to the observation platform in the crown is not practical. The tight headroom available—less than 9 ft (2.7 m)—ruled out a traction unit, as did the extremely tight shaftway, which measures only 2 ft, ½ in. × 4 ft, 10 in. (0.62 by 1.47 m). The car itself (see Fig. 33.12) measures only 1 ft, 11 in. × 3 ft, 10 in (0.58 by 1.17 m) (outside dimensions). Space was so tight that the drive was divided between two motors, both of which are mounted under the passenger compartment. Rack and pinion lifts are used both indoors and outdoors, primarily in industrial environments, for vertical transport of both passengers and materials.

33.12 RESIDENTIAL ELEVATORS AND CHAIR LIFTS

Although the special needs of the disabled have been widely and officially recognized in legislated requirements only since the late 1970s, the elevator industry has been providing for the mobility-impaired for years on a voluntary basis. Small private-residence elevators can double as wheelchair lifts and are available in a wide range of designs, including winding-drum units (Fig. 33.13), roped hydraulics, and worm and screw units. Standard traction designs are used infrequently due to the overhead space requirement. Similarly, standard hydraulic units requiring a plunger bore hole are rarely used.

In recognition of the fact that most residential elevators (and elevators intended primarily for use of the disabled in public and private buildings) are low-speed, limited-load units, the ASME developed a section of the elevator code (A17.1) to cover such units. The section applies to Limited Use/Limited Application (LU/LA) elevators, defined as "a power passenger elevator where the use and application is limited by size, capacity, speed and rise, intended primarily to provide vertical transportation for people with physical disabilities." The code section goes on to limit LU/LA elevators to a maximum size of 18 ft^2 (1.7 m^2), a load of 1400 lb (635 kg), a rise of 25 ft (7.6 m), and a speed of 30 fpm (0.15 m/s). Due to these limitations, safety requirements are



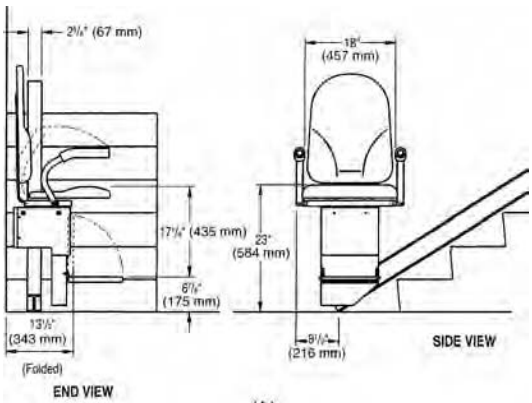
Cab sizes		
	A (width)	B (depth)
3 x 3	3 ft.	3 ft.
3 x 4	3 ft.	4 ft.
Special	To Suit (12 sq. ft. max. platform area)	

Fig. 33.13 *Isometric drawing of a typical residential elevator of the winding-drum design. Units of this type are usually limited to 500-lb (227-kg) car capacity, 40-ft (12.2-m) rise, and 30-fpm (0.15-m/s) speed. The car is rigidly attached in cantilever fashion to a rolling truck, which is raised and lowered by cables attached to the winding drum. The driving motor and winding drum shown here at the base of the assembly can be installed at any floor stop along the hoistway or overhead. Control is normally pushbutton automatic with limit-switch leveling. A 6-in. (150-mm) pit is required at the bottom of the hoistway. Door interlock, cable failure, and overrun safeties are standard items in such installations, which must meet elevator code requirements. (Courtesy of Waupaca Elevator Co., Inc.)*

different from those of standard traction elevators, drives may be different (e.g., winding-drum cable lifts), space requirements are smaller, and overall costs are considerably reduced. Elevators that exceed the defined limitations must conform to the requirements of the basic ANSI/ASME A17.1 elevator code.

Chair lifts and wheelchair platform lifts also come in a variety of designs. The chair lift shown in Fig. 33.14 uses a rack and pinion drive that permits

(a)



(b)

Fig. 33.14 *(a) Chair lift with a rack and pinion drive permits the lift to negotiate a turn in the stairs. This unit is limited to a live load of 300 lb (135 kg), runs at 25 fpm (0.13 m/s), climbs at any incline up to 51°, and is driven by a ½-hp (0.4-kW) motor. Maximum rise is 60 ft (18 m). (b) Dimensional data for the chair lift shown. (Courtesy of Access Industries, Inc.)*

it to negotiate a turn, as illustrated. For straight stair lifts, a winding-drum design similar to that used for residential elevators is often used. Other drives in use include worm gear and chain and screw worm and cog. The drive selection depends upon the load, rise, duty, and, of course, price. The wheelchair platform lift illustrated in Fig. 33.15 uses a ball screw drive. Other designs use some of the drives listed previously, including a roped-hydraulic drive for units requiring a large rise. The hydraulic scissor-jack type of wheelchair platform lift is most frequently found in public and institutional buildings because it is particularly applicable to short-rise, heavy-load, frequent-duty applications and requires minimal maintenance.

All of these units are covered by various sections of the elevator code and must be installed in accordance with code requirements, including safeties and controls. Residential units are normally arranged to operate on 120-V AC, although heavy-duty units may require 240-V service.

33.13 INNOVATIVE MOTOR DRIVES

A new elevator drive design developed by Otis utilizes a linear induction motor built into the counterweight frame. Motive power is therefore supplied at the counterweight, thus entirely eliminating the overhead traction machine and machine room. The inherent architectural, construction, energy usage, maintenance, and cost advantages of this elegant design make it an extremely attractive option for American building designers. A schematic diagram of the design is shown in Fig. 33.16. Other proprietary innovations have led to the common use of traction elevator systems that require no penthouse machine room, with the drive motor being incorporated into the hoistway space.

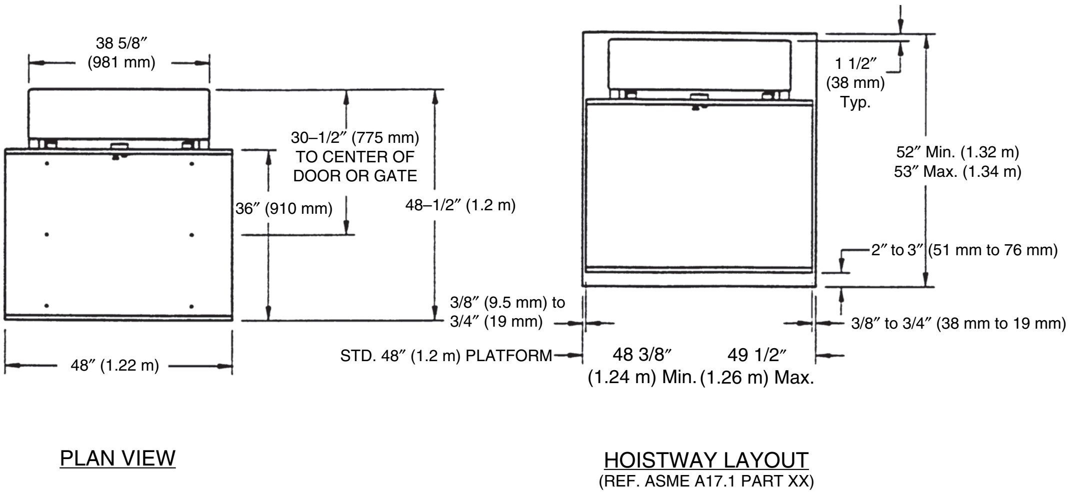
MATERIALS HANDLING

33.14 GENERAL INFORMATION

The materials-handling equipment briefly discussed herein finds application in commercial and institutional buildings. Industrial materials handling is an entirely separate subject beyond the scope of this section.

The need to transport material within a building has always existed, and, until about the late 1970s, it was done largely manually with mechanical assistance. Thus, offices used messengers, and hospitals used dumbwaiters, service elevators, conveyors, and chutes. The single exception to this

(a)



(b)

Fig. 33.15 *The wheelchair platform lift shown in (a) is designed for a maximum load of 750 lb (340 kg) and a maximum lifting height of 171 in. (4.34 m). The drive can be either a motor-driven recirculating ball screw unit or a 1:2 roped-hydraulic lift. Controls are mounted at the top of the right post of the gate frame. The unit is a straight-through design with gates at both ends. Dimensions are shown in (b). (Courtesy of Access Industries, Inc.)*

situation was the extensive use of pneumatic tube systems in large stores. Today's systems accomplish the same end—that is, the transfer of materials—but do so automatically and, in general, much more rapidly. The first cost of these systems is frequently high, but the reduction in labor and the increase in speed generally yield a short payback period combined with a marked rise in efficiency.

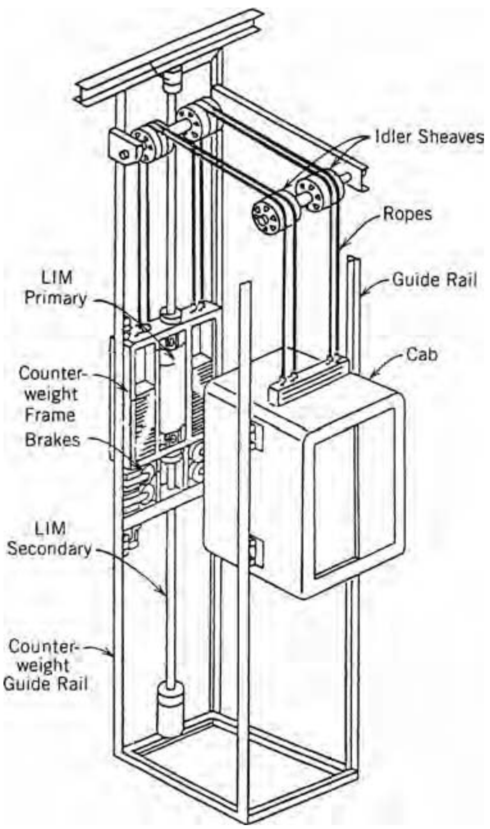


Fig. 33.16 *Schematic drawing of Otis Japan's linear induction motor (LIM) elevator design. Because the motor is built into the counterweight and supplies motive power linearly (vertically), the conventional overhead rotary traction machine is entirely eliminated, as is the machine room. The system operates more efficiently, quietly, and smoothly than the conventional design. (Courtesy of Otis Elevator.)*

Modern commercial materials-handling systems can be grouped into four broad categories:

1. *Elevator-type systems.* These are vertical-lift, car-type systems including the common dumbwaiter and ejection lifts (which are basically automated dumbwaiters).
2. *Conveyor-type systems.* These include horizontal and vertical conveyors.
3. *Pneumatic systems.* These include sophisticated pneumatic tube systems and pneumatic trash and linen systems.
4. *Other systems.* Systems that do not fit easily into any of the previously mentioned categories, including automated messenger carts and automatic track-type container delivery systems.

33.15 MANUAL LOAD/UNLOAD DUMBWAITERS

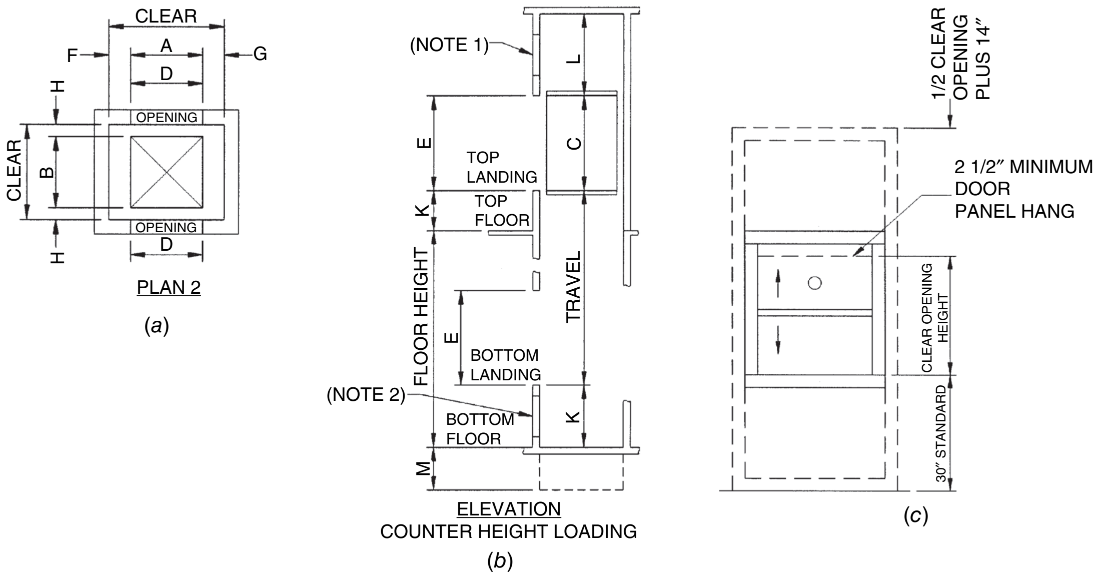
Dumbwaiters often provide the most convenient and economical means of transporting relatively small articles between levels. In department stores, such units transport merchandise from stock areas to selling or pickup counters; in hospitals, dumbwaiters often transport food, drugs, linens, and other small items. In multilevel restaurants and the like, dumbwaiters are almost always used for delivery of food from the kitchen and for return of soiled dishes.

Dumbwaiter cars are limited to a platform area of 9 ft^2 (0.84 m^2) and a maximum height of 4 ft (1.2 m). The car may be, and frequently is, compartmented by shelves. Normal speed ratings are 50 to 150 fpm (0.25 to 0.75 m/s), with a capacity of up to 500 lb (227 kg). Cars may be of the traction (counterweighted) or drum (direct pickup) type. Control is normally "call and send" between two floors, although multibutton selector switch or central dispatching arrangements are available for applications with more than two floors. Loading may be at floor, counter, or any other specified height (see Fig. 33.17 for typical layouts).

33.16 AUTOMATED DUMBWAITERS

These units are also known as *ejection lifts* because of the method of delivery (Fig. 33.18). They find their best application in institutions and other facilities that require rapid vertical movement of relatively large items. Thus, this device is ideally suited for delivery of food carts, linens, dishes, bulk-liquid containers, and so on. The load can be a cart (Fig. 33.19) containing the items being transported. At the delivery terminal, the item must be picked up and transferred horizontally to its final destination (if remote from the delivery point). Loading can be manual or automatic. Sophisticated ejection lifts use programmable controllers for automated loading, dispatch, and ejection; electronic sensors to determine whether space is available for a load; and automated return of the unloaded cart.

Payload capacity for cart systems is available up to 1000 lb (454 kg) and car speeds up to 350 fpm (1.8 m/s). Maximum cart size is approximately 32 in. W × 68 in. L × 70 in. H (0.8 by 1.7 by 1.8 m).



RATED LOAD (lb)	VOL. ■ ft³	COUNTER HEIGHT LOADING DIMENSIONS in.											
		CAR			DOORS ✱		HOISTWAY						
		A WIDTH	B DEPTH	C HEIGHT	D WIDTH	E HEIGHT	F	G	H	J	K ▲	L	M ✱✱
PLAN 1 OR 2 (MACHINE OVERHEAD OR BELOW) RATED SPEED 50–150 fpm													
APPLICATION – BULK SUPPLY, FOOD SERVICE (TRAY) & MATERIAL HANDLING													
100	8.33	20	24	30	20	30	6 1/2	7	5	3	30 ▲	48	6
200	12	24	24	36	36	24	6 1/2	7	5	3	30 ▲	48	12
300	17.5	30	24	42	30	42	6 1/2	7	5	3	30 ▲	48	18
400	30	36	30	48	48	48	6 1/2	7	5	3	30 ▲	48	24
500	36	36	36	48	48	48	6 1/2	7	5	3	30 ▲	48	24

✱ ONE OPENING MUST BE LARGER THAN THE CAR SIZE SO THE ASSEMBLED CAR CAN BE PLACED INTO, OR REMOVED FROM THE DUMBWAITER HOISTWAY.

✱✱ DEPTH OF PIT REQUIRED IF SLIDE DOWN TYPE DOORS ARE USED.

● 48 in. IF BI-PARTING HOISTWAY DOORS ARE USED.

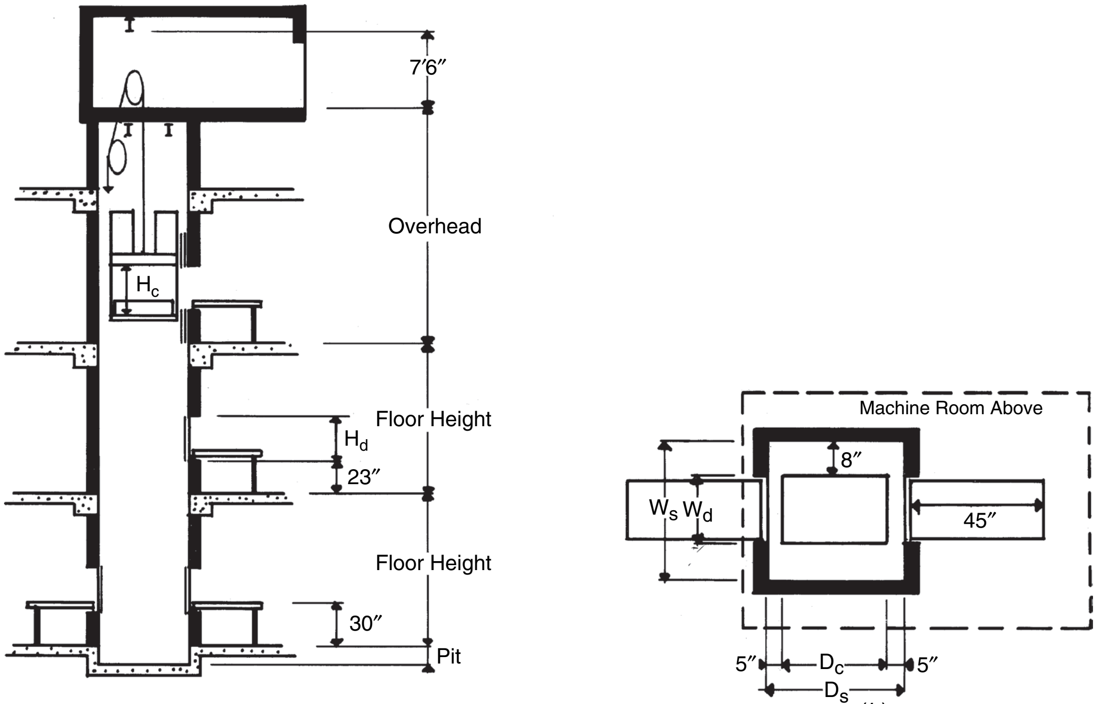
▲ IF BASEMENT MACHINE (DRUM OR TRACTION) 42 in.

■ CAR SIZES ARE OPTIONAL UP TO 9 ft² OF FLOOR AREA AND UP TO 48 in. HIGH.

NOTES
1. 2'-0" X 2'-0" ACCESS DOOR IF MACHINE ABOVE.
2. 2'-0" X 2'-0" ACCESS DOOR IF MACHINE BELOW.

(*d*)

Fig. 33.17 *Typical layout of a counter-height dumbwaiter with manual doors. The shaft openings (a, b) may be single (one side) or dual access. Doors can be biparting (c), slide up, or slide down. In addition to the sizes shown in the table (d), light-load cars rated 25 and 50 lb (11 and 23 kg) at 50 fpm (0.25 m/s) are available in standard designs. (Reproduced with permission of National Elevator Industry, Inc., 185 Bridge Plaza N., Fort Lee, NJ 07024; copyrighted 1992,* Vertical Transportation Standards.*)*



(*a*) **TOTE-MATIC** (*b*)

Lift Model	Capacity	Inside Car Dimensions			Inside Saft Dimensions		Hoistway Door Frame Dimensions		Pit (a)	Overhead (a)	Suggested Vertical Transportation Speed	
	Lbs.	WC	Dc	Hc	Ws	Ds	Wd	Hd			Landings	Feet per Minute
Tote-Matic CC-2	100	20"	31"	37"	40"	41"	20"	34"	12"	13′4"	7-10	150
											4-6	100
											2-3	50

(a) These figures must meet the requirements of ANSI/ASME 17.1 and local codes.

(*c*)

Fig. 33.18 *This automated dumbwaiter or vertical ejection lift is designed to eject (unload) a container automatically at a preselected station. (Note the dispatching station to the right of the doors.) The tote box is carried on an ejection conveyor, which electrically senses arrival at its destination and effects ejection. Station doors are automatically electrically operated. The dumbwaiter car drive mechanism is a counterweighted traction drive. Car capacity is 100 lb (45 kg), although containers are normally limited to 50 lb (23 kg) for ease of handling. Car speeds (see part c) are normally 50 to 150 fpm (0.25 to 0.75 m/s). A typical hoistway section (a) and plan (b) are shown. Vertical travel is not limited. Dimensions are provided in (c). (Courtesy of Courion Industries, Inc.)*

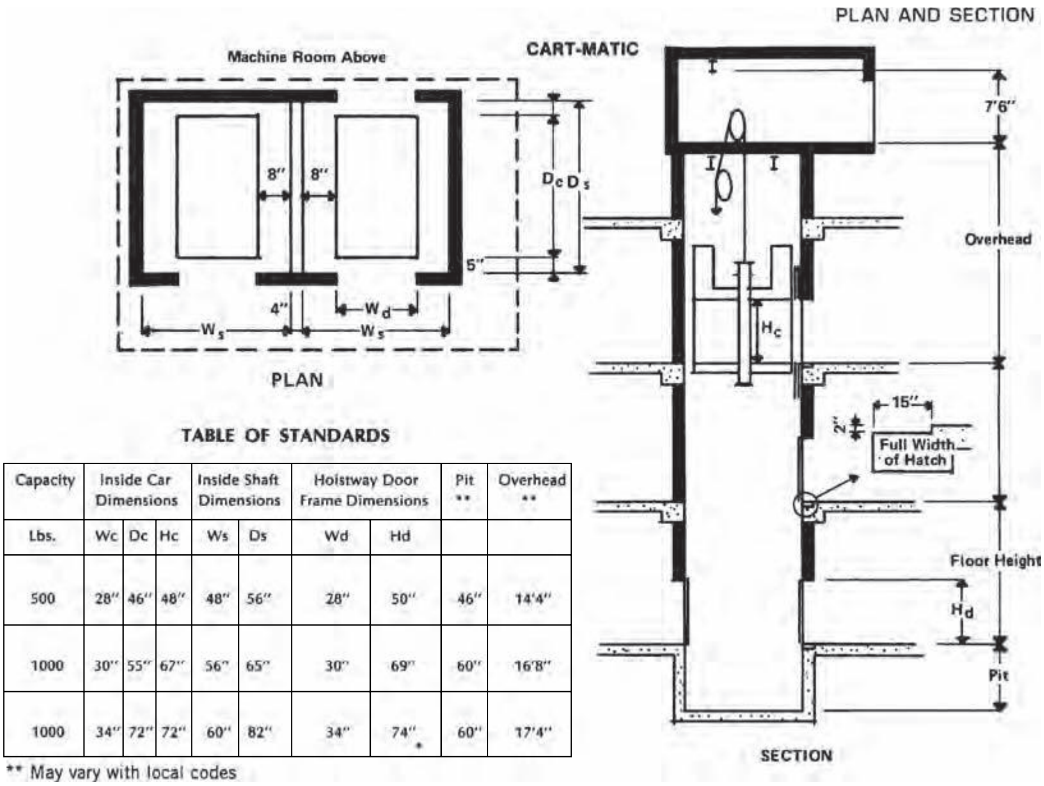
The round-trip time for a 200-fpm (1-m/s) unit with five loading stations is approximately 2 minutes. Major design considerations for these units are their relatively high cost and the large shaft area required.

33.17 HORIZONTAL CONVEYORS

Although horizontal conveyors find their best application in industrial facilities, they are also usable in commercial buildings such as mail-order houses, which require a continuous flow of material. Restrictions in application stem from inflexible right-of-way requirements, noise generation, and a degree of danger if conveyors are left unprotected or exposed to unauthorized persons. The cost is relatively low, and the capacity is virtually unlimited.

33.18 SELECTIVE VERTICAL CONVEYORS

The action of this system is similar to that of the automated dumbwaiter in that the system transfers



Capacity	Inside Car Dimensions			Inside Shaft Dimensions		Hoistway Door Frame Dimensions		Pit **	Overhead **
Lbs.	Wc	Dc	Hc	Ws	Ds	Wd	Hd		
500	28"	46"	48"	48"	56"	28"	50"	46"	14'4"
1000	30"	55"	67"	56"	65"	30"	69"	60"	16'8"
1000	34"	72"	72"	60"	82"	34"	74"	60"	17'4"

** May vary with local codes

Fig. 33.19 *Plan, section, and dimensions for a vertical ejection lift system (automated dumbwaiter). (Courtesy of Courion Industries, Inc.)*

materials vertically and automatically loads and unloads, but the similarity ends there. Vertical conveyors are constructed with a moving continuous-loop chain to which are attached carriages that pick up and deliver tote boxes (called *trays*). At sending and receiving stations, the operator places the items to be moved (up to 60 lb [27 kg]) in the tote box, "addresses" the box in one of several ways depending on the system, and places it at a pickup point. The first empty carriage on the chain picks up the box and delivers it to its address. Functions in modern vertical conveyors are monitored by a microprocessor, which tracks system operation and furnishes maintenance data and operational diagnostics. Drawbacks of this system are the large shaft required, noise, and cumbersome arrangements when interfacing with horizontal conveyors. The cost is moderate.

33.19 PNEUMATIC TUBES

This well-tried system will undoubtedly continue to be used where physical transfer of an item is required. Where information must be moved, electronic data reproduction has largely replaced the transfer of pieces of paper between two points. Pneumatic tube systems are available with a 2¼-to-6-in. (57-to-152-mm) range of tube diameters (special shapes are also used) and with single or multiple loops.

Whereas older systems were generally pressurized using a single large, noisy compressor, newer systems are computer-controlled, utilize a small blower in each of the zones, operate basically on vacuum but also on pressure, are relatively quiet, and are capable of being constructed in unlimited system length. Carriers travel at 25 fps (7.6 m/s).

The computerized control center provides information and control of all system components, including status, traffic data, station assignments, scheduling, and the like. Over all, pneumatic tube systems perform their task reliably, rapidly, and efficiently, at relatively low cost if installed during initial building construction. Typical system components are shown in Fig. 33.20.

(*a*)

(*b*)

Fig. 33.20 *(a) The recessed tube station illustrated is a full-facility combined sending and receiving point. Dispatching and receiving share the same pipe but operate independently and automatically. Arriving carriers (b) are decelerated by an air cushion and drop into the front bin on arrival. (b) Carriers are typically 3¾ in. D × 15½ in. L or 5¾ in. D × 16 in. L (95 x 394 mm and 146 x 406 mm) and are made of impact-resistant transparent polycarbonate plastic. Liners are used with fragile items. The bands around the carriers that maintain the air seal in the transport tubes are replaceable. (Courtesy of Swisslog Healthcare Solutions.)*

33.20 PNEUMATIC TRASH AND LINEN SYSTEMS

The purpose of this system is to rapidly move bagged or packaged trash and/or linens from numerous outlying stations to a central collecting point. Health codes require separate tubes for trash and linens. Linen systems are found generally in hospitals; trash systems in various facilities, frequently in conjunction with compactors. The system is basically a network of large pipes, negatively pressurized, with numerous loading stations throughout the building. Pipe sizes are 16, 18, or 20 in. (406, 457, 508 mm), operating at high static pressure. A system normally can handle only one unit load at a time, but moves it so quickly (20 to 30 fps [6.1 to 9.1 m/s]) that system capacity is large and delays are not encountered. Material placed into a loading station is picked up as soon as the previous load clears. Compressors are large and very noisy, requiring considerable space and acoustical isolation. In addition to the main vacuum system, a high-pressure air line is required to operate the doors, and sprinkler heads must be installed every few floors. Overall costs are low to moderate. For the specific task performed, a cheaper and more efficient transfer technique is difficult to find.

33.21 AUTOMATED CONTAINER DELIVERY SYSTEMS

This useful arrangement employs captive and secure containers locked onto a motorized carriage that, in turn, is locked onto a track system. Power for the motor in the carriage is picked off a third rail at 24 V DC. The entire assembly moves horizontally or vertically with equal ease. Containers move at a constant 120 fpm (0.6 m/s) horizontally, but more slowly on rises—depending upon the container load and the steepness of the rise. Containers are available in a number of shapes and volumes to suit the particular installation requirements. Two standard sizes are approximately 18 in. × 6 in. × 13 in. (457 × 152 × 330 mm) narrow profile and 18 in. × 12 in. × 8 in. (457 × 305 × 203 mm) low profile. The normal payload is 20 lb (9 kg), although for horizontal runs only, considerably heavier loads can be carried.

In simple single- or dual-track point-to-point or loop systems, right-of-way conflicts cannot occur, and routing is simply a matter of addressing the car. For complex systems involving loops and branches, routing is decided by a central computerized controller that finds the shortest route for each car (up to 250 cars per system), side-tracks cars, parks cars, and, in effect, operates a miniature railroad-type system. The system is easily added to a facility as a retrofit operation because of track flexibility and small size. Its major drawback is its high cost.

33.22 AUTOMATED SELF-PROPELLED VEHICLES

These robot battery-powered vehicles follow a route determined by a passive guidance floor tape. They can be arranged to interface automatically with vertical transport means (elevators) so that a route can cover various levels in a facility. The floor tape, which can be installed below carpets, is entirely passive. It determines only the path that the vehicle will follow. All sensing, instruction, motive power, and vehicle control are located on the vehicle itself, which can carry approximately a 300-lb (136-kg) payload and can operate a full 8-hour day without recharging its on-board batteries. Vehicle speeds are variable, ranging from 20 to 120 fpm (0.1 to 0.6 m/s). Programming of routes, stops, and vertical interfaces, changing of the cycle, and other functions are accomplished with an external programming device and an on-board programmable controller. Applications for an automated vehicle of this type are limitless: parts delivery and pickup in industrial facilities, food and supply distribution in hospitals, and mail and document pickup and delivery in offices are among its basic functions.

33.23 MATERIALS HANDLING SUMMARY

The foregoing brief overview broadly describes the types of equipment available. For each facility being planned, the architect must study the materials transfer problems, remembering that buildings not only handle and process but also generate material; an office building generates about 1 lb of waste per 100 ft^2 per day (4.8 kg per 100 m^2)—a prodigious amount in today's large office structures. This type of dry waste can be compacted, baled, and sold, unlike garbage and wet waste. In addition to considering the type of material being handled, there are factors of speed, scheduling, location of stations, labor and material costs, space requirements, noise generation, and energy requirements to address. To deal with all these factors in a large, complex facility is generally beyond the ability of the architect alone. Thus, expert advice from consultants who specialize in materials handling and from manufacturers' representatives should be sought.

CHAPTER 34

Moving Stairways and Walks

MOVING ELECTRIC STAIRWAYS

34.1 GENERAL INFORMATION

THE MOVING STAIRWAY, ALSO REFERRED TO AS an *escalator* or an *electric stairway*, was first operated at the Paris Exposition in 1900. Its modern successors deliver passengers comfortably, rapidly, safely, and continuously at constant speed and usually with no delay at the boarding level. The annoyance of waiting for elevators is eliminated. Also, no time is lost by acceleration, retardation, leveling, and door operation, or by passenger interference in getting in or out of the cars. Instead of requiring formal lobbies and hallways leading to a bank of elevators on each floor and a ride in a small, enclosed box, the electric stairway is out in the open, always in motion, inviting passengers to ride on an open, airy, observation-type conveyance that can never trap them due to equipment or power failure. In contrast to the generally utilitarian function of an elevator, an escalator also has a decorative/design function, and its open, observation characteristic is frequently used to expose the rider to specific visual panoramas.

34.2 PARALLEL AND CRISSCROSS ARRANGEMENTS

Moving stairs can be constructed in three ways, one of which is a *crisscross* arrangement and two are *parallel* arrangements. The aptness of these descriptive terms becomes evident in the diagrams and photos that follow.

The essential difference between the two basic arrangements is that in the crisscross arrangement, the upper and lower terminal entrances and exits to the up and down escalators are separated by the horizontal length of an escalator, whereas in either of the parallel arrangements the two escalators face in the same direction.

(a) The Crisscross Arrangement

This layout is simpler to visualize and also more common. It will be examined first (refer to Figs. 34.1*a* and 34.1*b*). Notice that the stair construction in both options is *identical*; the difference occurs in the direction of operation of the second level of stairs. In the spiral crisscross arrangement of Fig. 34.1*a*, the rider begins an upward trip on stair L1A and, by means of a 180° turn, continues the trip uninterrupted on stair L2A—traveling, effectively, in an upward spiral. The downward-traveling rider performs the same spiral trip on stairs L2B and L1B. This arrangement is rapid, pleasant, and very economical of space because the stairs nest into each other. It can be used for as many as five floors without excessive annoyance to the rider.

Now look at the arrangement of Fig. 34.1*b*. Reversing the direction of the second-level stairs L2A and L2B forces the upward-traveling passenger to leave L1A at the first upper landing and walk

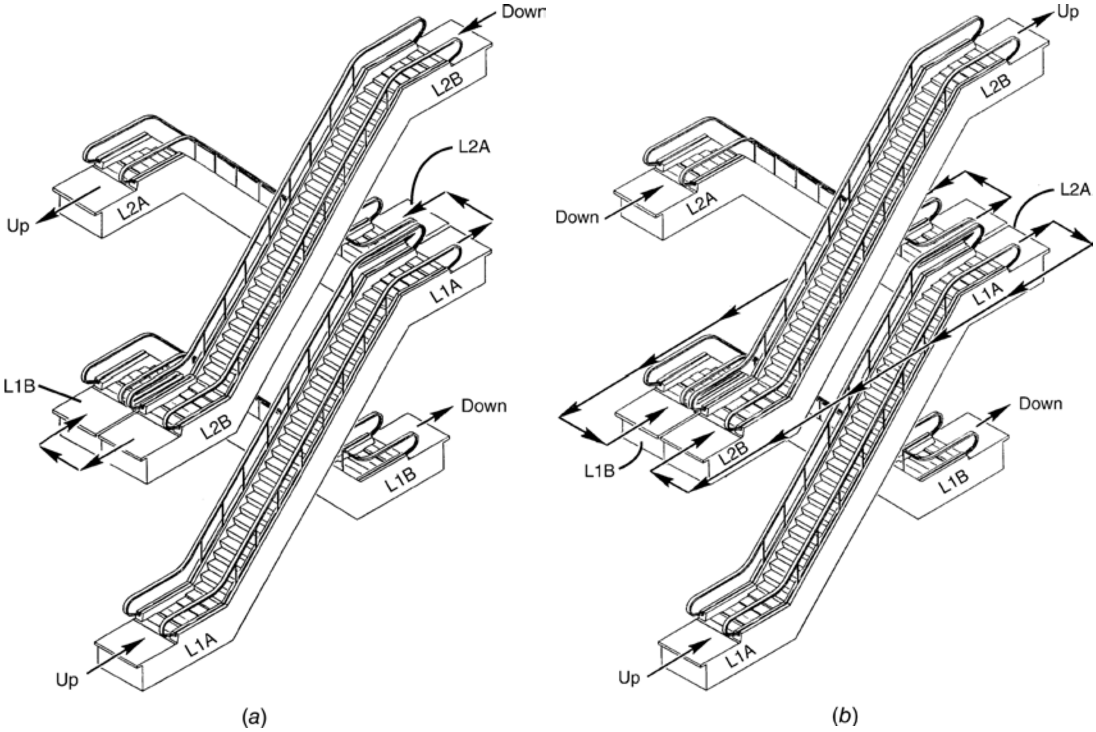


Fig. 34.1 *Escalators constructed in a crisscross arrangement. (a) When stairs L1A and L2A are operated in the up direction, a passenger from the lower terminal travels upward in a spiral, with only a turnaround at each level. The same is true for a down passenger. This system is called spiral operation, and the entire installation is referred to as crisscross spiral operation. (b) When the stair direction of upper-level stairs L2A and L2B is reversed, passengers at each intermediate landing (only one is shown) must traverse the entire horizontal stair length to reach the next stair traveling in the desired direction (see arrows on the drawing). As a result, this arrangement is known as crisscross walk-around operation. (Drawings courtesy of Otis Elevator Co.)*

around the entire length of the stair to continue the trip on L2B. Similarly, the downward-traveling passenger begins the trip on L2A but, at the first landing, must traverse the escalator length to reach the next down escalator L1B; hence the descriptive name *walk-around crisscross*. This arrangement requires floor space around the escalators, which is used in stores to display special sale merchandise. Indeed, this display purpose is the reason that stores force passengers to endure the potentially annoying walk-around.

A similar but generally much shorter and therefore less objectionable walk-around characterizes the spiral crisscross plan, where the escalators are separated by distance *D* (Fig. 34.2*a*). This distance is usually limited to about 10 ft (3 m) because any greater distance places the trip-continuation escalator out of sight, causing confusion and annoyance at the enforced walk. Separation of the escalators is frequently an architectural consideration and does have the advantage of easier mixing of riders entering at the various levels with riders making a continuous trip. Designers must, however, be continuously aware of the possibility of a negative reaction to the separation of escalators, which can be further reinforced when:

1. Insufficient floor space is provided for the transit between escalators, causing crowding, pushing, and delay.
2. Insufficient elevator service is provided for passengers wishing to travel at least three floors. This situation forces people to make a multistory escalator trip, which can be wearying, particularly when carrying parcels. If such a trip is further lengthened by an enforced walk-around at each floor, it becomes a source of severe irritation, often sufficient to keep customers away from the store.

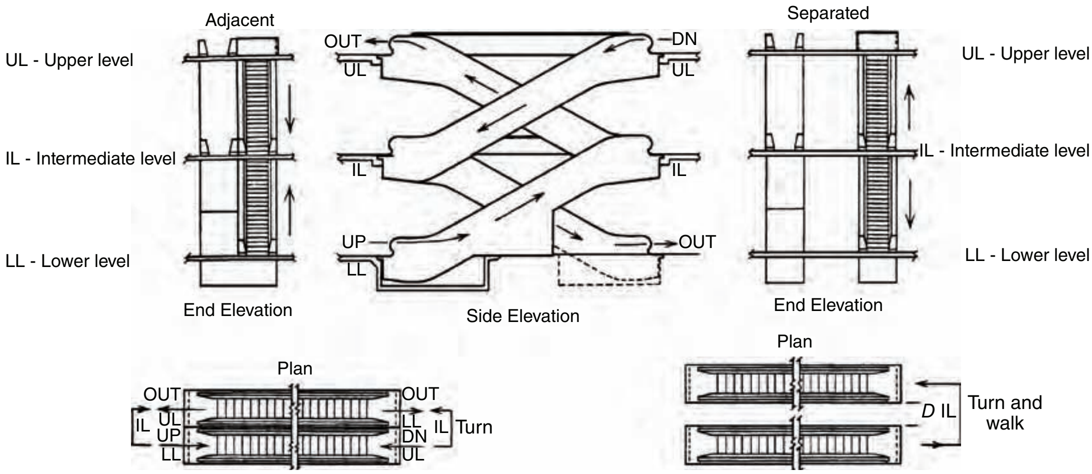


Fig. 34.2 *Side and end elevations and plan views of the crisscross escalator arrangements. In the spiral operation mode (see text), separating the escalators forces the rider to walk distance D to continue a trip. In the walk-around operation mode, escalators are frequently separated to provide a walk-around path.*

Figure 34.2 shows the plan and elevation of the crisscross arrangement for both spiral and walk-around operation, since, as shown, construction is identical for both. Figures 34.3 and 34.4 illustrate the crisscross plan.

(b) Parallel Escalators

This configuration requires more floor space than the crisscross arrangement and is therefore used less often. As noted, it is constructed in either of two

Fig. 34.3 *Bank of glass balustrade escalators with mirrored sides in a spiral operation, crisscross plan. Note the dividers at the turnaround at the intermediate level, whose function is to guide traffic smoothly, either away from the escalator or to the turn point. This effectively eliminates undesirable bunching and crowding. (Photo courtesy of O&K Rolltreppen, Germany.)*

Fig. 34.4 *Crisscross design applicable to either spiral or walk-around operation. The horizontal area in the right foreground can be used to display impulse-buying merchandise to walk-around riders during holiday seasons, after which operation can be returned to the spiral mode. (Photo courtesy of O&K Rolltreppen, Germany.)*

designs: the parallel spiral arrangement, shown in Fig. 34.5*a*, or the stacked parallel arrangement, with forced walk-around, shown in Fig. 34.5*b*. The principal advantage of the parallel arrangement is its impressive appearance, as can be seen in Figs. 34.6 through 34.9 The stacked arrangement must be used with caution due to the inconvenience to the rider of an enforced long walk-around to continue the trip. This arrangement is found most often in mass-purchase facilities and in malls. In department stores or malls this arrangement is much less objectionable, as many people are there to browse and window-shop rather than to purchase and leave, as is the case in a single-purpose store. In a multistory store, the inconvenience of this walk—which is frequently compounded by the crowds of people that normally congregate at special sale merchandise displays and counters—rapidly engenders annoyance. Thus, the stacked arrangement is seldom used above two floors (one such walk-around), and when it is used above two floors, riders can be expected to gravitate to elevators.

Escalators between two contiguous levels do not present the continued trip problem and therefore are frequently used in the parallel arrangement. This configuration is particularly common in public buildings, transportation terminals, and other heavy traffic areas, where the advantage of a single location for the entrance to the bank of escalators eliminates confusion and the safety hazard engendered by hesitant, confused riders in heavy traffic.

The consideration of division of rider traffic between elevators and escalators in a store is important. The general philosophy of store owners is to make escalators the primary means of vertical transportation for the obvious reason of merchandise exposure. As a result, elevators are frequently placed at one or both ends of a store, whereas the escalator banks are central. However, care must be taken to provide sufficient elevatoring in stores exceeding three floors, particularly in stores using the stacked or walk-around crisscross plans, because of the inconvenience of multifloor escalator trips discussed previously.

34.3 LOCATION

Because escalators are constantly moving and are generally part of a horizontal and vertical trip, they must be placed directly in the main line of traffic. This is in contrast to an elevator bank, which, being a vertical transportation unit, can be set off as an

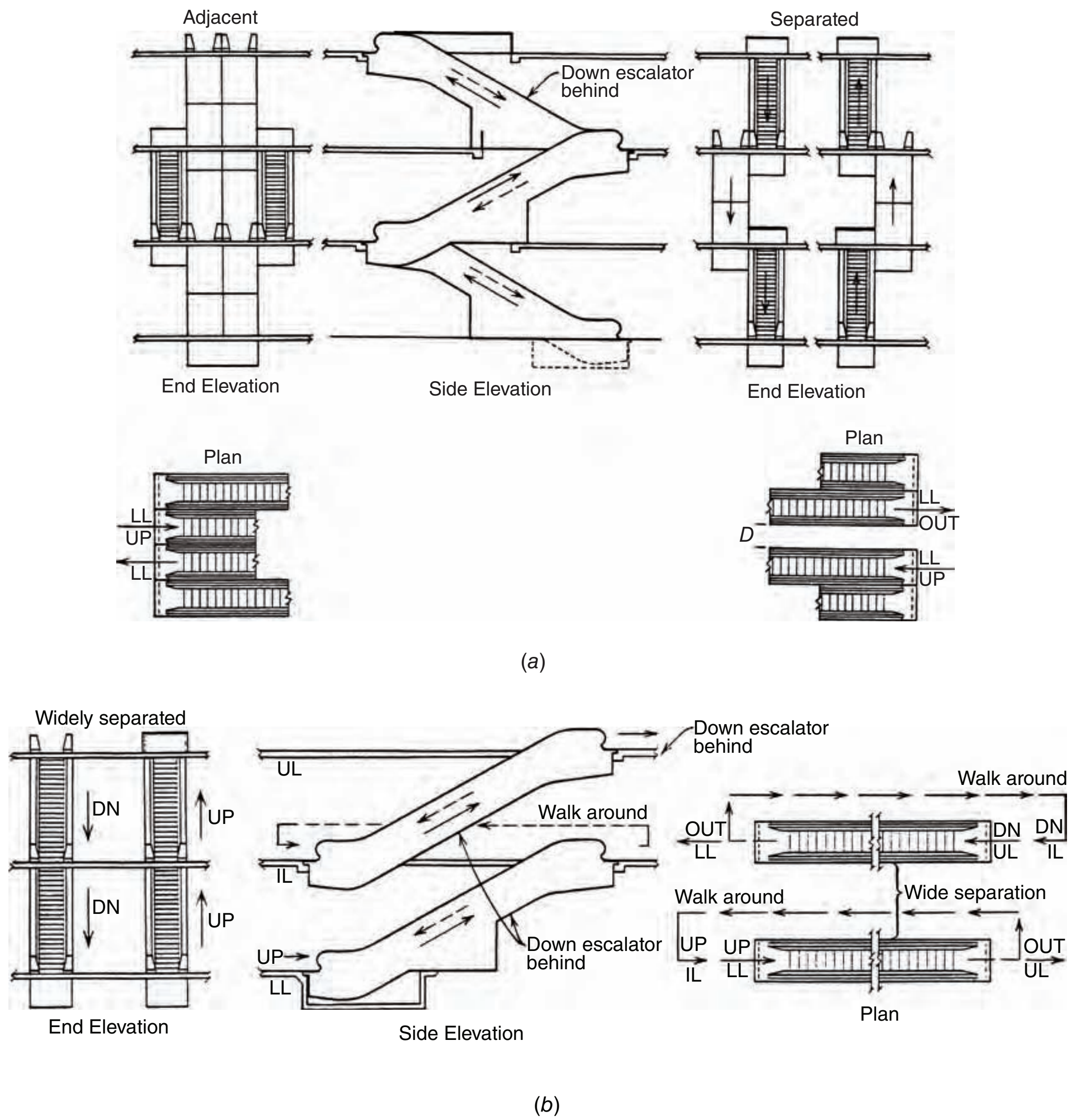


Fig. 34.5 *Side and end elevations and plan views of escalators in (a) spiral parallel and (b) stacked parallel arrangements. In the spiral parallel arrangement (a) the separation has no effect on the rider, who simply makes a turn to continue in the same up or down direction. In the stacked arrangement (b), the rider must traverse the entire length of the escalator at each level in order to continue, since the escalators are stacked vertically on each floor.*

element on its own for people to approach and utilize. Escalators must therefore be placed in the area served, often with a dominating presence. This allows potential riders to immediately:

1. Locate the escalators
2. Recognize the individual escalator's destination
3. Move easily and comfortably toward the escalator

One of the most ineffective ways to handle traffic movement is to inadequately mark escalator destinations. The resultant milling about, false starts, and constant inquiries can be observed in such buildings, and in stores where large displays block an originally open line-of-sight.

Sufficient lobby space must be provided at the base for queuing where anticipated, particularly at discharge points. A restricted or poorly marked

Fig. 34.6 *An unusual design of stacked parallel escalators with a forced walk-around in a continuous trip. The exposed truss and drive elements, combined with a transparent balustrade, add considerable visual interest to the installation. (Photo courtesy of O&K Rolltreppen, Germany.)*

Fig. 34.7 *An unusual installation of parallel escalators adapted to a long four-story building. In the more common instance of a building that is taller than it is long, the escalators are stacked as in Fig. 34.6 Here the design is adapted to the large central court/atrium, with offset stepped landings and entrances to the buildings. (Photo courtesy of O&K Rolltreppen, Germany.)*

Fig. 34.8 *Escalators in transportation terminals are subject to periods of very heavy use. To avoid crowding at the entrance to the up (left) moving stair, the balustrade is effectively extended with a glass-sided divider. Passengers on the down (right) escalator are guided by large overhead signs and a standing sign at the base, as well as balustrade extension to avoid hesitation and bunching. Note also the large open area in front of both units. (Photo courtesy of O&K Rolltreppen, Germany.)*

discharge area causes passenger hesitation and traffic backup. Because the escalator discharges continuously, backup of traffic is dangerous and therefore intolerable. This is particularly crucial in theaters and stadiums, where even momentary hesitation during peak traffic periods can be disastrous. To avoid this, four design steps, in descending order of importance, are taken:

1. Provide well-marked escalators with sufficient traffic-carrying capacity.
2. Provide collecting space at intermediate landings so that passenger pressure can be relieved.
3. Provide a physical divider at intermediate landing turnaround points that guides riders away from the discharge point, and provide adequate space (and time) for riders either to leave at that level or to follow the guide around and continue the trip (see Fig. 34.2).
4. Provide a slight setback for the next escalator so that the necessary 180° turn can readily be negotiated.

At the exit terminus, an escalator should discharge into an open area with no turns or choice

Fig. 34.9 *Among the longest moving stairways in Europe are those installed in the Stockholm subway system. This parallel bank of three escalators is 230 ft (70 m) long with a 108-ft (33-m) rise. Unlike American standards of 30° incline, 100-fpm (0.51-m/s) speed, and 32- or 48-in. (0.81- or 1.22-m) size, these units are at 27.3° incline, 147.6-fpm (0.75-m/s) speed, and 40-in. (1.02-m) width. (Photo courtesy of O&K Rolltreppen, Germany.)*

of direction. When such clarity is absolutely unachievable, *large*, unambiguous signs should make hesitation unnecessary (see Fig. 34.8). The landing space beyond the escalator newels should be a minimum of 8 ft (2.4 m) for 32-in. (0.81-m) units and 10 ft (3 m) for 48-in. (1.22-m) units for a standard 100-fpm (0.5-m/s) speed. For escalators that will be reversed to accommodate change in traffic direction, this landing space must be provided at the top and bottom.

The crisscross arrangement has the advantages of lower cost, minimum floor space being occupied, and the least structural requirements. The parallel arrangement, being less efficient and more expensive, has as a compensating virtue a very impressive appearance that strongly draws people to it. For this reason it is frequently employed, particularly in banks of three or four units, in transportation terminals (see Figs. 34.8 and 34.9). In such large installations, flexibility is maintained by operating all but one escalator in the direction of heaviest traffic. Reversibility of escalators provides this most desirable feature.

34.4 SIZE, SPEED, CAPACITY, AND RISE

Moving stairs are built according to manufacturers' and industry standards, and are therefore available in standard designs. However, all major manufacturers also produce special designs for particular applications. The data that follow refer to standard designs.

All escalators in the United States are installed at an angle of 30° from the horizontal, with a minimum vertical clearance of 7 ft (2.1 m) for escalator passengers. The 30° inclination means that the rise is equal to 57% of the unit's projected floor area for its inclined portion. The length of the horizontal portions of the stairway depends on the specific design. To meet the Americans with Disabilities Act (ADA) requirements, elongated newels with at least two horizontal treads before the landing plate are needed. Today, although the maximum linear speed permitted by the safety code (ANSI/ASME 17.1) is 125 fpm (0.64 m/s), the industry has standardized on a single speed of 100 fpm (0.5 m/s).

ANSI/ASME 17.1 now defines the *width* of an escalator as the width of the stair tread (in inches). The previous width designation referred to the distance between balustrades, a figure difficult to define because of design variations. That measurement is now called *size*. The standard sizes and widths are:

Escalator Size in. (m)	Tread Width in. (m)
32 (0.81)	24 (0.61)
48 (1.22)	40 (1.02)

Table 34.1 lists theoretical, nominal (design), and observed average escalator passenger capacities. Maximum loads assume approximately 1¼ persons per tread for a 32-in. (0.81-m) unit and almost 2 persons per tread for a 48-in. (1.22-m) unit. In actuality, maximum capacity is approached only during peak-load periods in transportation terminals and stadiums. At other times, a full (heavy) load is represented by the nominal capacity figure, and an average (long period) load by the observed capacity figure. Although a 40-in. (1.02-m) tread can indeed carry two persons, psychological factors, plus physical ones such as bulky clothing, packages, purses, and briefcases, militate against such loading. As a result, on a 40-in.- (1.02-m)-wide tread, one person uses each step in a diagonal pattern, and on 24-in. (0.61-m) stairs one person occupies every other tread.

Some major manufacturers make two standard models (not styles) of moving stairs: (1) a standard-duty unit intended for general indoor use, which provides low to medium rise, and (2) a heavy-duty, sturdier unit intended for all-weather heavy-traffic use such as at transport terminals. The latter, because of heavier construction, can provide a greater maximum rise than standard units. Maximum rise for off-the-shelf design units varies among manufacturers. Approximate maximum figures are given in Table 34.2.

Specially designed units are available with rises of up to about 60 ft (18 m). In escalator design all the motive power is delivered at one point; that is, the drive motor drives the main chain, which drives the top sprocket, which drives the step chain, which pulls up the steps, causing the entire assembly to move. This arrangement is suitable for moderate rises of up to approximately 25 ft (7.6 m); beyond that, the design becomes increasingly inefficient. As the rise increases, the loads on all the drive components, including chains and sprockets, increase sharply. Furthermore, to accommodate the heavier equipment, truss width increases, as do wellway size and balustrade decks. For rises above 25 to 35 ft (7.6 to 10.7 m)—depending on unit width—the drive motor is too large to fit inside the truss and requires a separate machine room below the truss, with attendant cost. These factors combine to limit standard escalators to a maximum rise of 60 ft (18 m), which varies slightly among manufacturers.

34.5 COMPONENTS

The major components of a standard escalator installation are shown in Fig. 34.10. Safety devices are discussed in Section 34.6.

The truss is a welded steel frame that supports the entire apparatus (see Fig. 34.4). The tracks are steel angles attached to the truss on which the step rollers are guided, thus controlling the motion of the steps. The sprocket assemblies, chains, and machine provide the motive power for the unit, somewhat similar to the chain drive of a bicycle.

The handrail is driven by sheaves powered from the top sprocket assembly. It is synchronized with the tread motion to provide stability to riding

TABLE 34.1 Escalator Passenger Capacity

			Passengers per Hour		
Size in. (m)	Tread Width in. (m)	Speed fpm (m/s)	Maximum[a]	Nominal[b]	Observed[c]
32 (0.81)	24 (0.61)	100 (0.51)	5200	4000	2300
48 (1.22)	40 (1.02)	100 (0.51)	9000	6750	4500

[a]Theoretical maximum (see text).
[b]Heavy loading (see text).
[c]Average long-period loading.

TABLE 34.2 Approximate Maximum Escalator Rise

Unit Size in. (m)	Type	Supports	Maximum Rise ft (m)
32 (0.81)			24 (7.3)
	Standard	Ends	
48 (1.22)			16 (4.9)
32 (0.81)		Ends	30 (9.1)
	Standard	and	
48 (1.22)		center	20 (6.1)
32 (0.81)			24 (7.3)
	Heavy	Ends	
48 (1.22)			18 (5.5)
32 (0.81)		Ends	40 (12.2)
	Heavy	and	
48 (1.22)		center	20 (6.1)

passengers and support for entering and leaving passengers. Handrails disappear at inaccessible points at the newels. The balustrade assembly is designed for maximum safety of persons stepping on or off the escalators.

Transparent balustrades are made of tempered glass and are frequently referred to as *crystal balustrades*. In these units, the handrail is pinch-driven within the truss. In addition to metal and glass balustrade materials, fiberglass, wood, and various plastic materials are used.

The control cabinet, which is normally located near the drive machine, contains malfunction indicators in addition to the drive controls. The cabinet may also contain a microprocessor malfunction analyzer and communication means for transmitting escalator operating conditions to a central control point. Operation of an emergency stop button, which is wired to the controller and placed near or on the escalator housing at both ends, stops the drive machine and applies the brake. Key-operated control switches at the top and bottom newels start, stop, and reverse the stairway.

34.6 SAFETY FEATURES

Protection of passengers during normal operation is ensured by a number of safety features associated with moving stairways:

- Handrails and steps travel at exactly the same speed (100 fpm [0.51 m/s]) to ensure steadiness

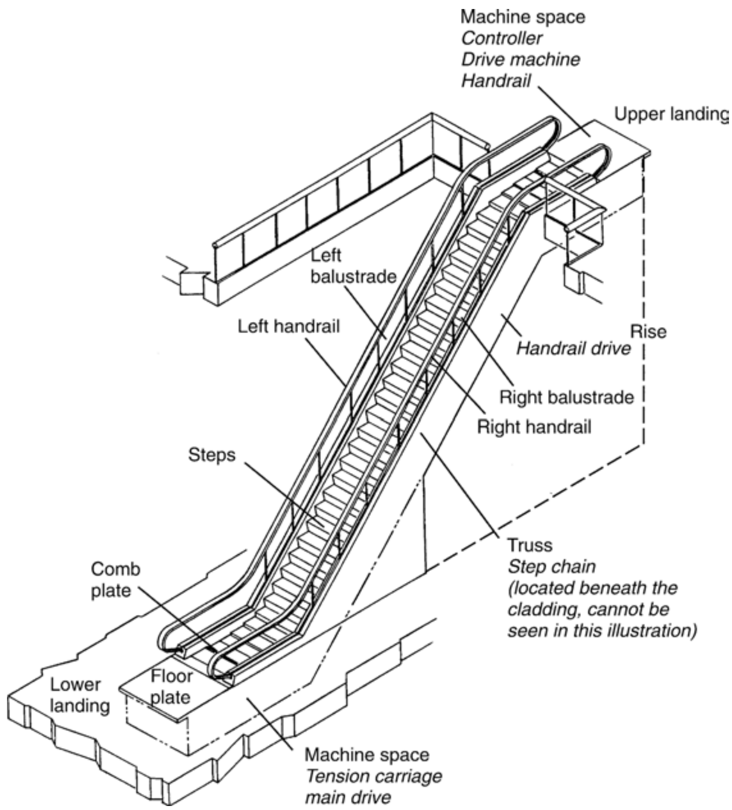


Fig. 34.10 *View of a standard escalator showing the principal parts. (Drawing courtesy of Otis Elevator Co.)*

and balance and to aid passengers stepping on or off the combplates.
- The steps are large and steady, and are designed to prevent slipping.
- Step design and step leveling with the combplates at each landing prevent passengers from tripping upon entering or leaving the escalator. This is accomplished with two or three (depending upon the manufacturer) horizontal steps at either end of the escalator.
- The balustrade is designed to prevent catching of passengers' clothing or packages. Close clearances provide safety near the combplates and step treads.
- Adequate illumination is provided at all landings, at the combplates, and completely down all stairways. Some escalator designs provide built-in lighting, as discussed in Section 34.8.
- An automatic service brake will bring the stairway to a smooth stop if:
  - The drive chain or the step chain is broken or abnormally stretched
  - A foreign object is jammed into the handrail inlet, between the skirt guard and step, or between steps, causing them to separate
  - A power failure occurs
  - The emergency stop button is operated (one is located at either end of the escalator)
  - Any of the fire safety system devices operates (see Section 34.7)
  - A tread sags, rises, or breaks
  - A drive motor malfunction occurs

In case of overspeed or underspeed, an automatic governor shuts down the escalator, prevents reversal of direction (up or down), and operates the service brake.

If the escalator is stopped by operation of a safety device, passengers can then walk the steps as they would on any stationary stairway.

34.7 FIRE PROTECTION

Four methods of providing protection in case of fire near escalators are available: the rolling shutter, the smoke guard, the spray-nozzle curtain, and the sprinkler vent. One of these methods is required by code when more than two floors are pierced. Figure 34.11 illustrates how the wellway at a given

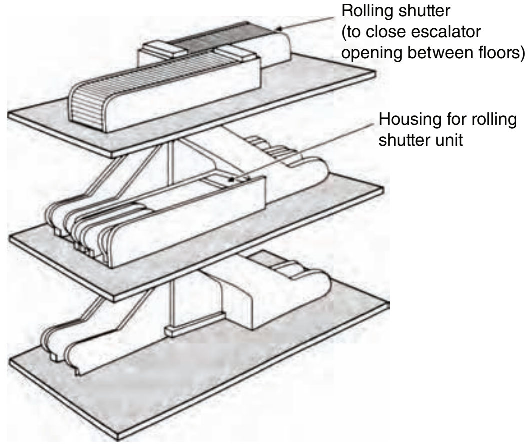
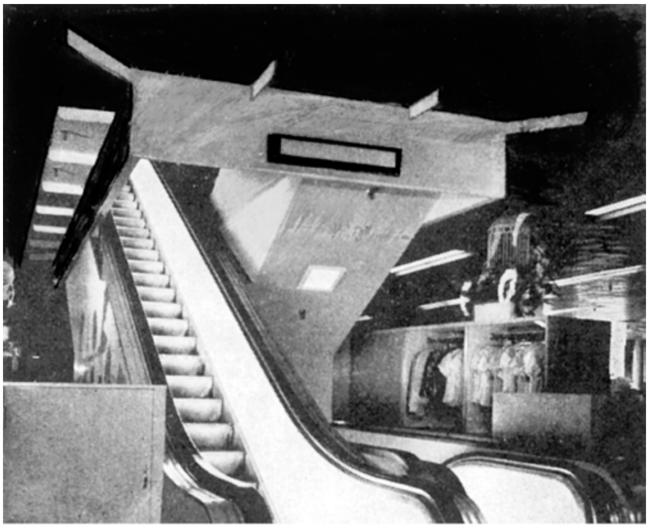


Fig. 34.11 *Rolling-shutter method of wellway fire protection. (Reproduced with permission from NFPA's Fire Protection Handbook®, 20th edition, Copyright© 2008, National Fire Protection Association. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)*

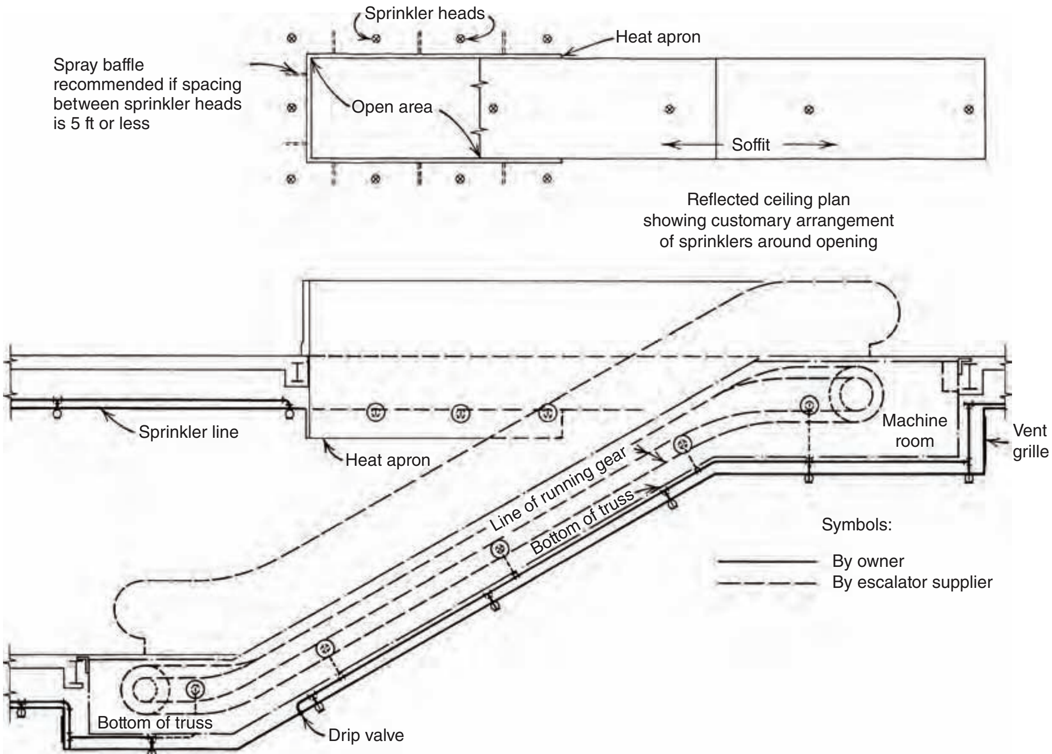
floor level may be entirely closed off by a fire shutter, thus preventing draft and the spread of fire upward through escalator wells. Temperature and smoke detectors automatically actuate the motor-driven shutters. The shutter in Fig. 34.11 is shown at the third-floor level, but other shutters may be installed at the tops of horizontal wellway openings at any floor. This approach appears to be little implemented in North America, but is fairly common in the United Kingdom and Europe.

Figure 34.12 illustrates the smoke-guard method of protection. It consists of fireproof baffles surrounding the wellway and extending downward about 20 in. (510 mm) below the ceiling level. Smoke and flames rising upward to the escalator floor opening meet a curtain of water automatically released from conventional sprinkler heads, shown at the ceiling level. The baffle is a smoke and flame deflector. The vertical shields between adjacent sprinklers ensure that the spray from one will not cool the nearby thermal fuses, preventing the opening of adjacent sprinklers.

The spray-nozzle curtain of water (not shown) is similar to the smoke-guard protection. Here, closely spaced, high-velocity water nozzles form a compact water curtain to prevent smoke and flames from rising through the wellways. Automatic thermal or smoke relays open all nozzles simultaneously.



(*a*)



(*b*)

Fig. 34.12 *(a) Smoke-guard method of fire protection for a 32-in. (0.81-m) moving stairway, crisscross type. The escalator floor opening (per floor) is approximately 4 ft, 4 in. × 14 ft, 8 in. (1.3 by 4.5 m). (b) Reflected ceiling plan and section showing baffle and sprinkler layout. (Courtesy of Otis Elevator Co.)*

The sprinkler-vent fire control system is shown in Fig. 34.13. The fresh air intake housed on the roof contains a blower to drive air downward through escalator floor openings, while the exhaust fan on the roof creates a strong draft upward through an exhaust duct; this duct in turn draws air from separate ducts just under the ceiling of each moving stairway floor opening. Three such separate

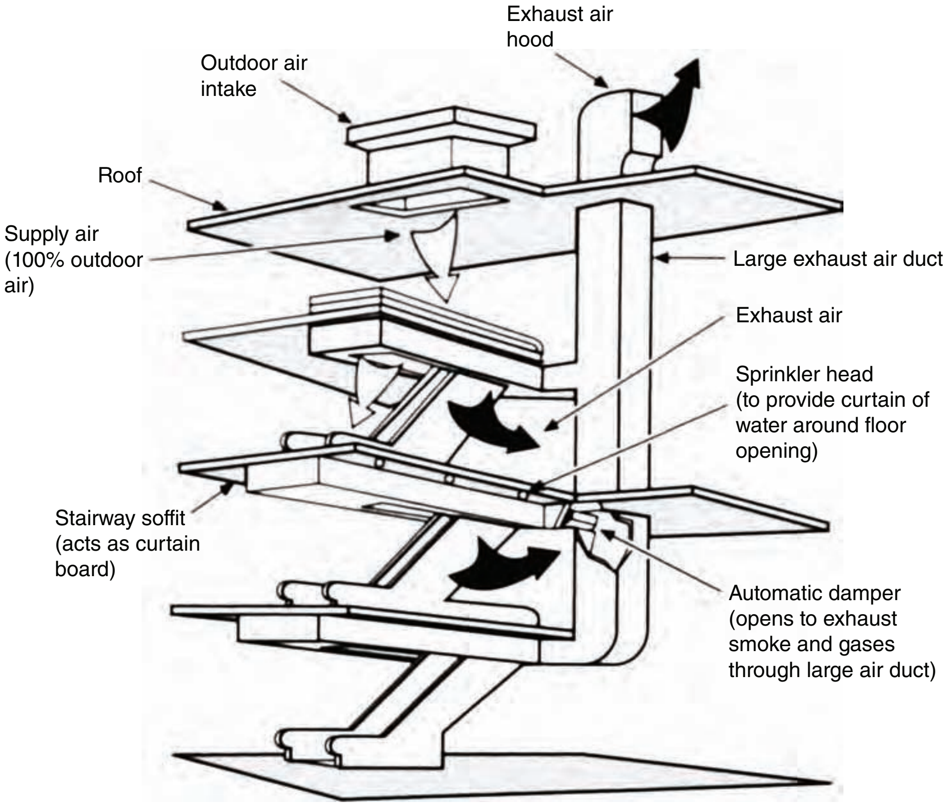


Fig. 34.13 *Sprinkler-vent fire protection for escalator openings—an exception (with control) to the rule against perforations in floors. (Reproduced with permission from NFPA's Fire Protection Handbook®, 20th edition, Copyright© 2008, National Fire Protection Association. This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.)*

wellway ducts are shown. Each duct has a number of smoke-pickup relays that automatically start the fresh air fans. The usual spray nozzles on the ceiling near the stairways aid in quenching the fire.

34.8 LIGHTING

Adequate illumination of a moving stairway, particularly at the landings, is important from decorative as well as safety standpoints. In a stairwell-type installation, where general-area lighting does not provide sufficient illumination for an escalator, lighting appropriate to the adjacent illumination is installed on the ceiling above the escalator, with special emphasis on lighting the combplate. In Fig. 34.9, banks of fluorescent lamps are placed across the escalator bank at frequent intervals along the rise. Note the additional lighting provided at the combplate. Two different lighting treatments of similar installations are shown in Figs. 34.14 and 34.15 (see also the balustrade lighting in Fig. 34.16).

34.9 ESCALATOR APPLICATIONS

1. Main floor locations should be chosen in the direct flow of traffic to ensure maximum use.
2. Vertical arrangements should be designed to accomplish specific intents, such as exposure of merchandise, maximum passenger capacity, and maximum accessibility to various areas.
3. Reversibility of an electric stairway should be considered in applications where major traffic flow is unidirectional. Light traffic in the reverse direction can be handled by a normal fixed stair adjacent to the escalator (see Fig. 34.16). Similarly, a bank of two escalators can operate either both up, both down, or one up and one down, to

Fig. 34.14 Lighting for escalator treads and combplates is supplied by a continuous fluorescent strip at the base of the balustrade in the Seattle Public Library. (© Alison Kwok; all rights reserved.)

Fig. 34.15 A continuous fluorescent source is placed under the handrail of the crystal balustrade in this covered mall in West Germany. Note the additional light at the base for illuminating the combplate. (Photo courtesy of O&K Rolltreppen, Germany.)

handle variable traffic conditions in areas such as office buildings and transportation terminals.

4. Exterior escalators can provide an interesting and economical way of transporting people to elevated entry points in a building (see Fig. 34.16).

34.10 ELEVATORS AND ESCALATORS

Elevators and escalators should be considered together—as a single solution in vertical transportation—for the particular facility being designed. In this connection, and particularly in the case of modernization, Fig. 34.17 provides a comparison of options.

In certain facilities, there are times when demand for vertical transportation is so great that elevators are not a feasible solution. A prime example is a school building. During class change, virtually the entire building population moves, with as many as 80% moving between floors. Since class change time is at most 10 minutes, the only reasonable solution is the combined use of fixed and

Fig. 34.16 An all-weather exterior electric stairway is often the best solution to an elevated building entrance or exit. Note the elongated left balustrade, which prevents bunching at the escalator entrance, and the fluorescent fixture built into the balustrade, which provides nighttime tread lighting. (Photo courtesy of O&K Rolltreppen, Germany.)

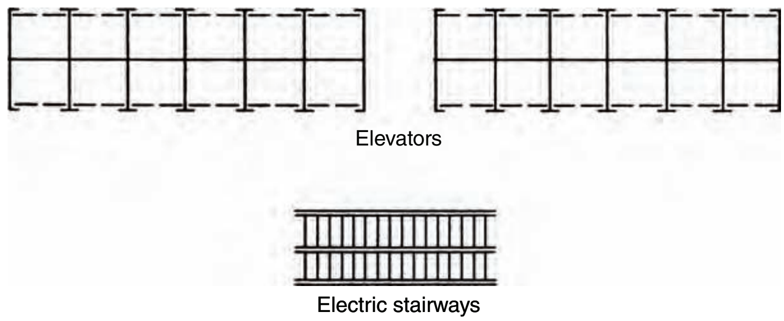


Fig. 34.17 Comparative space requirements for equivalent passenger-handling capacity. Note the substantial space savings offered by escalators.

moving stairs. In other buildings, such as multifloor stores, the escalator provides for short trips of one or two floors, and the elevator generally transports passengers traveling three or more stories.

A comparison of travel time between escalators and elevators is of interest. For an escalator, using a normal speed of 100 fpm (0.51 m/s), a 12-ft (3.7-m) floor height requires 14.4 seconds for travel plus about 5 to 6 seconds to transfer to the next section, for a total of approximately 20 seconds. Thus, a four-story trip would take approximately 75 seconds. A similar elevator trip would take at most 60 seconds. The additional escalator time is not noticed amidst the activity of boarding, turning, and riding. A trip of more than four stories, however, becomes tiresome, and all the more so when there is an enforced walk-around at each floor.

34.11 ELECTRIC POWER REQUIREMENTS

Standard North American electric stairways are driven by three-phase, 60-Hz, AC induction motors at standard voltages (208, 230, and 460 V). Approximate horsepower data for drive motors are shown in Table 34.3.

It is recommended that no more than four escalators be served by a single electric feeder, and further, that not all the escalators in an installation, whatever the number, be served from the same feeder.

Since one cannot be trapped on an escalator, emergency power is rarely required. Ventilation for the machinery should be supplied for approximately 40% of the power, expected to be dissipated as heat. Thus, a 10-hp (7.5-kW) motor would require the dissipation of 0.40 × 10 × 2500 (Btu/h hp), or approximately 10,000 Btu/h (2.9 kW).

TABLE 34.3 Typical Standard-Duty Escalator Motor Sizes

Escalator Maximum Size in. (m)	Rise ft (m)	Size of Motor hp (kW)
32 (0.81)	14 (4.3)	5 (3.7)
	22 (6.7)	7½ (5.6)
	30 (9.1)	10 (7.5)
48 (1.22)	10 (3.1)	5 (3.7)
	15 (4.6)	10 (7.5)
	20 (6.1)	15 (11.2)

34.12 SPECIAL-DESIGN ESCALATORS

Like elevators, escalators of nonstandard design are available on special order. These include units with slopes other than 30°, speeds other than 100 fpm (0.51 m/s), and rises beyond normal. The most unusual of these special designs is the curved escalator, which made its debut overseas and is now available in the United States. This design, which solves the very common problem of directing passengers to make a 90° turn as they leave the escalator, is an engineering tour de force. The entire drive mechanism had to be designed anew because the tread speed along the inside curve must be lower than that on the outside curve. The handrail drive was less of a problem since the handrail is narrow, and therefore speed variation within it is minimal.

34.13 PRELIMINARY DESIGN DATA AND INSTALLATION DRAWINGS

At the preliminary design stage, the architect requires rough dimensional and structural data for an intended escalator installation. Since at this stage of design a specific manufacturer for the stairs has not yet been selected, and because these data vary from one supplier to another, the information in Fig. 34.18 and Table 34.4 is given as a range that covers most of the major manufacturers. Similar data are available from the National Elevator Industry, Inc. Once construction contracts have been awarded and an escalator supplier selected, exact data on space requirements and structural reactions are available from the vendor. On these, two “working points” (see Fig. 34.18) are identified. From these two points, all other measurements are made—that is, locating the centerline of the truss sections, placing the lower and upper landing truss support beams, and so on.

TABLE 34.4 Typical Escalator Dimensions

Dimension	Range (I-P)	Range (SI)
A	13′ 2″ to 16′-10″	4.0 to 5.1 m
B	7′-5″ to 9′-4″	2.3 to 2.9 m
C	5′-9″ to 7′-6″	1.8 to 2.3 m
D	3′-3″ to 4′-2″	1.0 to 1.3 m
E	3′-3″ to 3′-9″	1.0 to 1.1 m
F	12′-5″ to 14′-10″	3.8 to 4.5 m
G	2′-11″ to 3′-1″	889 to 940 mm
H	2′-7″ to 2′-9″	787 to 838 mm
I: 32″ (812 mm)	3′-11″ to 4′-6″	1.2 to 1.4 m
I: 48″ (1220 mm)	5′-3″ to 5′-8″	1.6 to 1.7 m
J	0	0
K	2′-11″ to 3′-2″	889 to 965 mm
L: 32″ (812 mm)	4′-0″ to 4′-4″	1.2 to 1.3 m
L: 48″ (1220 mm)	5′-3″ to 5′-10″	1.6 to 1.8 m
M: 32″ (812 mm)	2′-0″	610 mm
M:48″ (1220 mm)	3′-4″	1.0 m
N	1′-9″ to 2′-2″	533 to 660 mm
O	3′-6″ to 4′-0″	1.1 to 1.2 m

Note: See Fig. 34.18 for locations of dimensions A through O.

34.14 BUDGET ESTIMATING FOR ESCALATORS

The cost of an escalator includes the cost of the associated mechanical and electrical equipment, plus shipping and installation charges. The manufacturer provides expert engineering and a field erector who supervises the installation.

A tabulation of *relative* escalator prices, on a base of 100 monetary units, is given in Table 34.5. Prices for units with a rise above 35 ft (10.7 m) increase very rapidly and depend upon the type of unit used. The designer is referred to suppliers for quotes on all units. To these figures must be added the cost of the contractor’s work, wellway protection, lighting, outside balustrades, and plaster.

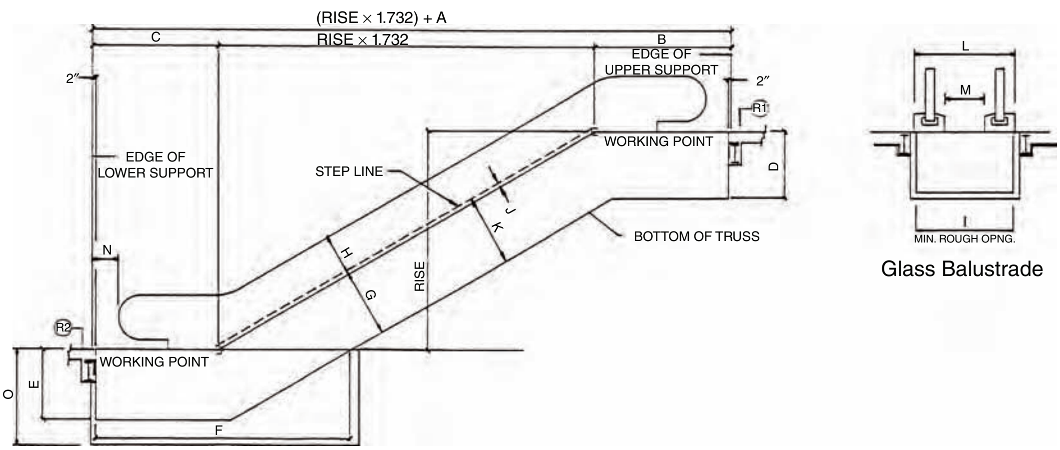


Fig. 34.18 *Escalator dimensional data in a range representing most of the major manufacturers. See Table 34.4 for I-P and SI values. These data should be used for preliminary planning only.*

TABLE 34.5 Relative Escalator Prices

	Size	
Rise ft (m)	**32 in. (0.81 m)**	**48 in. (1.22 m)**
14 (4.3)	100[a]	118
16 (4.9)	103	121
18 (5.5)	105	124
20 (6.1)	108	127
22 (6.7)	111	130
24 (7.3)	113	133
26 (7.9)	115	135
28 (8.5)	118	138
30 (9.1)	120	141

[a]Base price figure is 100 monetary units for the shortest, narrowest, slowest unit (i.e., 14-ft [4.3-m] rise, 32 in. [0.81 m] wide). All units are 100 fpm (0.51 m/s). Add 5% for a glass balustrade for any unit.

MOVING WALKS AND RAMPS

34.15 GENERAL INFORMATION

Moving walks and ramps are different from moving stairways in application, function, construction, and capacity. Escalators have as their primary function the movement of large numbers of people vertically, when such vertical distance does not exceed approximately five stories. A moving stair performs this specific transportation function extremely well with minimum cost, space, and maintenance.

When vertical transportation of wheeled vehicles and large parcels is required, the use of an electric stairway is at best awkward, if not impossible. For such functions and others discussed in the following sections, the moving ramp serves very well.

Unlike the elevator and escalator, the moving walk or ramp serves a dual function, that is, horizontal transportation only or a combination of horizontal and vertical transportation. For the purposes of this discussion, a moving *walk* is defined as having an incline not exceeding 5°, where the principal function is horizontal motion, and inclined motion is incidental to the horizontal. A moving *ramp* is a device with an incline limited by code to 15°, where vertical motion is generally more important than the horizontal component. It should be understood that a walk and ramp are physically the same device, but differently applied.

34.16 APPLICATION OF MOVING WALKS

The principal uses of moving walks, also known as *autowalks*, are to:

1. Eliminate and/or accelerate burdensome walking
2. Eliminate congestion
3. Force movement
4. Easily transport large, bulky objects

Anyone who has walked the seemingly endless distances in a major airport, carrying or dragging a heavy suitcase, can appreciate the necessity for a moving walkway. For this reason, air transport terminals have become major users of this item (see Fig. 34.19). Other transportation facilities, such as rail and ship terminals, also can often find excellent applications for a moving walk, since much heavy and bulky luggage is moved in these areas.

The apparent distance compression that moving walks can provide permits the placement of parking areas in more distant locations. Thus, a store can extend its parking area with no annoyance to patrons who must make the long trip to their cars with bulky packages or shopping carts. These advantages are all the more appreciated by persons with a walking impediment.

A second application of walks, as noted previously, is the routing of traffic to avoid congestion, milling about, and lost time and motion. This is particularly applicable in transportation terminals, where people are always traveling in opposite directions through the same—and often restricted—area, such as in "fingers" leading from airplanes to the main air terminal.

Moving walks are also useful to move people past a display window or some other point where congestion caused by stopping is undesirable. This "movement of objects" application demonstrates clearly that the moving walk is simply a large conveyor belt, regardless of its construction.

34.17 APPLICATION OF MOVING RAMPS

The moving ramp that combines horizontal and vertical movement is principally applicable:

1. To move persons and wheeled vehicles vertically

Fig. 34.19 *Two pairs of moving walks. At the Chicago O'Hare International Airport, horizontal moving walks ease circulation congestion and the hassle of traveling with heavy carry-on items. The walkway connecting the concourses is additionally complemented with vibrant colors that change in pattern, designed to be an enlivening experience for travelers. (© Alison Kwok; all rights reserved.)*

2. To move persons who lack the agility required to use an escalator
3. To vertically move large, bulky objects

Ramps have found an important field of application in multilevel stores (Fig. 34.20) where escalators are not feasible for shopping-cart users. Such stores may also utilize rooftop parking that is made accessible to cart users via a moving ramp. Since luggage carriers are not easily used on escalators, transportation terminals, which are almost always multilevel, also find extensive application for moving ramps (Fig. 34.21).

Fig. 34.20 *Unusual angular design of multiple ramps in a shopping mall in Brisbane, Australia. The use of ramps rather than escalators permits shopping carts and bulky packages to be moved with ease between the building levels. (Photo courtesy of O&K Rolltreppen, Germany.)*

34.18 SIZE, CAPACITY, AND SPEED

The speed, physical dimensions, and therefore passenger capacity of walks and ramps are not as extensively standardized as is the case with escalators. Manufacturers utilize several different tread widths,

Fig. 34.21 *Multiple inclined ramp installation in a European department store (three up, two down). Of interest in this installation are the level entries, the lighted balustrades, the ease with which shopping carts are handled on the wide pallet, and the use of the space between the transparent balustrades for merchandising. (Photo courtesy of O&K Rolltreppen, Germany.)*

combined with various speeds and ramp angles of incline. The combinations are designed to suit the application. Furthermore, since the maximum permissible walk ramp speed varies with the angle of slope, and with the design of the entering point, passenger capacity ratings vary with each design. By code, higher speeds are allowed for a level entrance than for a sloping entrance, for the simple reason that a level entrance is easier to board. Tables 34.6 and 34.7 and Fig. 34.22 give data for typical units.

Since capacity varies with width, speed, and type of entrance, exact capacity figures must be obtained for each specific design. The maximum practical length at present is approximately 1000 ft (305 m), with longer units under consideration. Wide autowalk units (55 in. [1.4 m]) are now extensively used in transportation terminals, since they permit passengers with luggage trolleys who walk on the moving walkway to easily pass other passengers with luggage carts who prefer to stand still and move at the relatively slow rate of 100 to 130 fpm (0.51 to 0.66 m/s)—about half of normal walking speed. Recent installations of such wide autowalks are found at Heathrow, Gatwick, and Munich airports, among others.

TABLE 34.6 Maximum Permissible Operating Speeds of Moving Ramps

	Maximum Speed fpm (m/s)	
Angle of Incline	**Level Entrance**	**Sloping Entrance**
0–3°	180 (0.9)	180 (0.9)
3–5°	180 (0.9)	160 (0.8)
5–8°	180 (0.9)	140 (0.7)
8–12°	140 (0.7)	130 (0.65)
12–15°	140 (0.7)	125 (0.625)

TABLE 34.7 Moving Walks/Ramps: Commercial Ratings

Angle	Pallet Width in. (m)	Ramp Speed fpm (m/s)
0–3° Walk	32 (0.81)	100 (0.5), 130 (0.65), 150 (0.75)
	40 (1.02)	100 (0.5), 130 (0.65), 150 (0.75)
	62 (1.58)	90 (0.45), 100 (0.5), 130 (0.65)
10°, 11°, 12° Ramp	32 (0.81)	100 (0.5), 130 (0.65)
	40 (1.02)	90 (0.45), 100 (0.5), 130 (0.65)

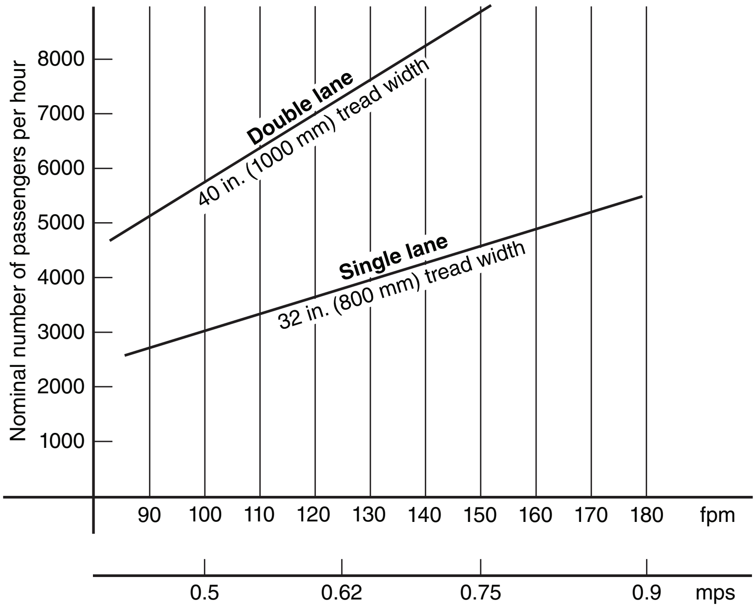


Fig. 34.22 *The capacity of moving walks varies with speed, angle of incline, and tread width. The capacity shown is for the maximum incline permitted at that walk speed. Because of the requirement for handrail support, tread widths greater than double lane are not often utilized.*

34.19 COMPONENTS

Moving walks are manufactured in only one design: a derivative of the escalator, which uses a flattened pallet in place of a step. In all other respects—the drive mechanism, safeties, brake, handrails, and so on—the unit is similar to an escalator. Preliminary layout data and detailed plans are, as with moving stairs, available from vendors, who frequently are the same vendors that supply escalators.

References and Resources

Goetz, A. 2003. *Up, Down, Across*. Merrell Publishers. London, UK.

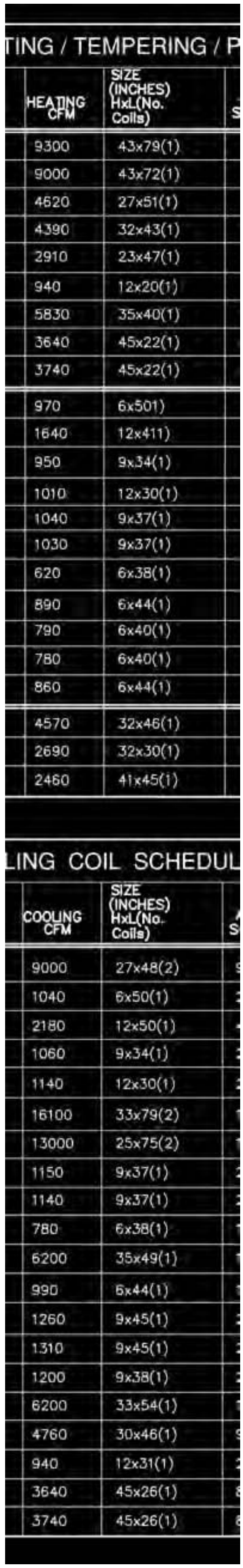
Otis Elevator Company. http://www.otis.com/site/us/pages/EscalatorsMovingWalks.aspx?menuId=3

Strakosch, G.R. 1983. *Vertical Transportation, Elevators and Escalators*, 2nd ed. John Wiley & Sons. Hoboken, NJ.

Strakosch, G.R. (ed.) 1998. *The Vertical Transportation Handbook*. John Wiley & Sons. Hoboken, NJ.

PART X

APPENDICES



TING / TEMPERING / P

HEATING CFM	SIZE (INCHES) HxL(No. Coils)
9300	43x79(1)
9000	43x72(1)
4620	27x51(1)
4390	32x43(1)
2910	23x47(1)
940	12x20(1)
5830	35x40(1)
3640	45x22(1)
3740	45x22(1)
970	6x501)
1640	12x411)
950	9x34(1)
1010	12x30(1)
1040	9x37(1)
1030	9x37(1)
620	6x38(1)
890	6x44(1)
790	6x40(1)
780	6x40(1)
860	6x44(1)
4570	32x46(1)
2690	32x30(1)
2460	41x45(1)

LING COIL SCHEDUL

COOLING CFM	SIZE (INCHES) HxL(No. Coils)
9000	27x48(2)
1040	6x50(1)
2180	12x50(1)
1060	9x34(1)
1140	12x30(1)
16100	33x79(2)
13000	25x75(2)
1150	9x37(1)
1140	9x37(1)
780	6x38(1)
6200	35x49(1)
990	6x44(1)
1260	9x45(1)
1310	9x45(1)
1200	9x38(1)
6200	33x54(1)
4760	30x46(1)
940	12x31(1)
3640	45x26(1)
3740	45x26(1)

The purpose of this part of the book is to present important reference and ancillary data (often extensive) in a separate, easily accessed area that does not detract from the flow of the text in the chapters. The appendices are:

A. Metrication, SI Units, and Conversions
B. Climatic Conditions for the United States, Canada, and Mexico
C. Solar and Daylighting Design Data
D. Solar Geometry
E. Thermal Properties of Materials and Assemblies
F. Ventilation and Infiltration
G. Heating and Cooling Design Guidelines and Information
H. Standards/Guidelines for Energy- and Resource-Efficient Building Design
I. Annual Solar Performance
J. Economic Analysis
K. Sound Transmission Data
L. Design Analysis Software

APPENDIX A

Metrication, SI Units, and Conversions

A.1 GENERAL COMMENTS ON SI UNITS

The building industry in the United States has been slow (glacially so) in adopting the metric (more accurately, Le Système International d'Unités, or SI) system of units for many reasons. The rest of the world, however, is generally fully SI (or metric). Many professional societies use a mixture of I-P (inch-pound, previously "English" units) and SI units as a means of addressing their international audiences. Many older units are also so entrenched that changing them is a seemingly impossible task. This book attempts to provide dual units where feasible, but that is not always possible. For this reason, tables of conversions and approximations are presented in the following material to enable the user to work with both systems. This appendix also presents some facts that should make use of the SI system a bit easier.

A.2 SI NOMENCLATURE AND SYMBOLS

For a full discussion of the SI system, see *AIA Metric Building and Construction Guide*, edited by S. Braybrooke (John Wiley & Sons, New York, 1980) and the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE) publication "SI for HVAC&R" (May 1999), available from the ASHRAE website (http://www.ashrae.org/). The units in common use include the basic SI staples—the meter, kilogram, and second (MKS)—plus a host of derived, supplementary, and non-SI units such as the pascal (pressure), radian (solid angle), and kilowatt-hour (energy). Also, multiple and submultiple units such as the liter, metric ton, and millibar are so common that they stand as separate units instead of being expressed as 10^{-3} m^3, 10^3 kg, and 10^{-2} Pa.

Table A.1 lists SI unit prefixes with their accepted symbols. Symbols do not change in the plural. That is, 6 millimeters is written as 6 mm and 20 kilograms is written as 20 kg. All units and prefixes except Fahrenheit and Celsius are in lowercase when written out (as in megaton or meter).

Table A.1 Common SI Unit Prefixes

Multiples and Submultiples	Prefixes	Symbols
1 000 000 000 = 10^9	giga	G
1 000 000 = 10^6	mega	M[a]
1 000 = 10^3	kilo	k[a]
100 = 10^2	hecto[b]	h
10 = 10	deka	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c[a]
0.001 = 10^{-3}	milli	m[a]
0.000 001 = 10^{-6}	micro	μ[a]
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p

[a]Most commonly used.
[b]A hectare is a square hectometer (i.e., 10^4 m^2).

A.3 COMMON USAGE UNITS

1. *Length*: meter (m), kilometer (km), millimeter (mm), micrometer (μm), nanometer (nm). The micrometer (μm) is also called a micron in the U.S.
2. *Area*: square meter (m^2), hectare (ha).
3. *Volume*: cubic meter (m^3), liter (L).
4. *Flow*: cubic meters per second (m^3/s).
5. *Velocity—Airflow*: meters per second (m/s).
6. *Weight*: kilogram (kg), gram (g).

The SI system clearly differentiates between mass (kg) and force (kg • m/s^2), the latter being given a separate name and symbol, the newton (N). Weight is not used, because it is a force that depends upon acceleration and is therefore variable. However, the construction industry largely continues to use the terms *mass*, *weight*, and *force* interchangeably.

7. *Force*: newton (N), kilonewton (kN). A newton is the force required to accelerate 1 kg at 1.0 m/s^2.
8. *Pressure*: pascal (Pa), kilopascal (kPa). A pascal is a newton per square meter (N/m^2).
9. *Energy, Work, Quantity of Heat*: joule (J), kilojoule (kJ), megajoule (MJ). A joule is a watt-second (W • s).
10. *Temperature*: degree Celsius (°C), degree kelvin (K).

SI temperature in degrees kelvin is not as commonly used as °C (*Celsius* is the accepted term; *centigrade* is obsolete). The Celsius and kelvin scales are subdivided equally but start at different points—that is, 0 K is −273.15°C. Therefore, to determine kelvin from Celsius, simply add 273.15. Increments are equal because of equal subdivisions; that is, a change of 10 K is the same as a 10C° change. Because of its common usage in design work, a Fahrenheit/Celsius conversion chart is given in Fig. A.1.

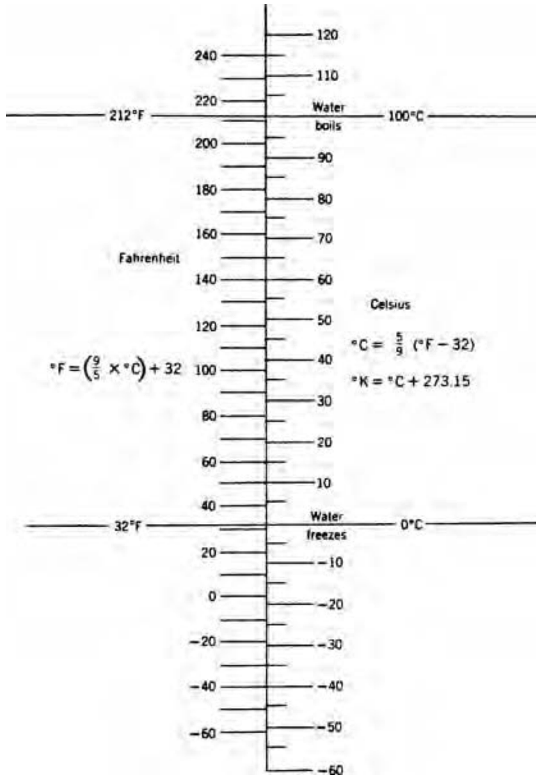


Fig. A.1 *Conversion nomograph: Fahrenheit temperature/Celsius temperature.*

11. *Illumination*: see Table 13.1.
12. *Acoustics*: see Table 24.16.
13. *CGS/MKS Conversions*: see Table 24.16.
14. *Abbreviations*: See Table A.2.
15. *Approximations*: See Table A.3.

A.4 CONVERSION FACTORS

Table A.4 is an alphabetized list of useful conversion factors. Decimal notation has been used in this table (versus scientific notation), that is, 0.00378 versus 3.78×10^{-3} or 3.78E3.

Table A.2 Typical Abbreviations: All Systems of Units

atmospheres	atm	gallons	gal
British thermal units	Btu	gallons per hour	gph, gal/h
British thermal units per hour	Btu/h	gallons per minute	gpm, gal/min
calorie	cal	grams	g
cubic feet	cf, ft^3	hectares	ha
cubic feet per minute	cfm, ft^3/min	horsepower	hp

Table A.2 Typical Abbreviations: All Systems of Units *(Continued)*

cubic feet per second	cfs, ft^3/s	inches	in.
cubic meters	m^3	inches of mercury	in. Hg
feet	ft	joules	J
feet per second	fps, ft/s	kilocalories	kcal
kilograms	kg	miles per hour	mph
kilograms per second	kg/s	millimeters	mm
kilojoules	kJ	millimeters of mercury	mm Hg
kilometers	km	newtons	N
kilometers per hour	kph, km/h	ounces	oz
kilonewtons	kN	pounds	lb
kilopascals	kPa	pounds of force	lbf
kilowatts	kW	pounds per cubic foot	lb/ft^3
kilowatt-hours	kWh	second	sec, s
liters	L	square feet	ft^2
liters per second	L/s	square inches	$in.^2$
megajoules	MJ	square meters	m^2
meganewtons	MN	watts	W
megapascals	MPa	watts per square meter	W/m^2
meters	m	yards	yd
meters per second	m/s		

Table A.3 Common Approximations

Approximate Common Equivalents					
1 inch	=	25 millimeters	1 millimeter	=	0.04 inch
1 foot	=	0.3 meter	1 liter	=	61 cubic inches
1 yard	=	0.9 meter	1 meter	=	3.3 feet
1 mile	=	1.6 kilometers	1 meter	=	1.1 yards
1 square inch	=	6.5 square centimeters	1 kilometer	=	0.6 mile
1 square foot	=	0.09 square meter	1 square centimeter	=	0.16 square inch
1 square yard	=	0.8 square meter	1 square meter	=	11 square feet
1 acre	=	0.4 hectare	1 square meter	=	1.2 square yards
1 cubic inch	=	16 cubic centimeters	1 hectare	=	2.5 acres
1 cubic foot	=	0.03 cubic meter	1 cubic centimeter	=	0.06 cubic inch
1 cubic yard	=	0.8 cubic meter	1 cubic meter	=	35 cubic feet
1 quart	=	1 liter	1 cubic meter	=	1.3 cubic yards
1 gallon	=	0.004 cubic meter	1 liter	=	1 quart
1 ounce	=	28 grams	1 cubic meter	=	250 gallons
1 pound	=	0.45 kilogram	1 kilogram	=	2.2 pounds
1 horsepower	=	0.75 kilowatt	1 kilowatt	=	1.3 horsepower

Table A.4 Useful Conversion Factors: Alphabetized

Multiply	By	To Get
acres	4047	square meters
atmospheres	33.93	feet of water
atmospheres	29.92	inches of mercury
atmospheres	760.0	millimeters of mercury
Btu (energy)	0.252	kilocalories
Btu (energy)	1.055	kilojoules
Btu/h (power)	0.2931	watts
Btu/h ft^2 (energy transfer)	3.155	watts per square meter
Btu/°F (heat capacity)	1.897	kilojoules per kelvin[a]
Btu/lb °F (specific heat)	4.184	kilojoules per kilogram per kelvin[a]
Btu/h°F ft (thermal conductivity[b])	1.729	watts per kelvin[a] per meter
Btu/h °F ft^2 (thermal conductance[c])	5.673	watts per kelvin[a] per square meter
Btu/°F day (building load coefficient, BLC)	0.022	watts per kelvin[a]
Btu/°F day ft^2 (load-collector ratio, LCR)	0.236	watts per kelvin[a] per square meter
cubic feet	0.02832	cubic meters
cubic feet	7.481	gallons
cubic feet	28.32	liters
cubic feet per minute	0.4719	liters per second
cubic feet per second	28.32	liters per second
cubic inches	16.39	cubic centimeters
cubic meters	35.32	cubic feet
cubic meters	1.308	cubic yards
cubic meters	264.2	gallons
cubic yards	0.765	cubic meters
feet	0.3048	meters
feet	304.8	millimeters
feet per second	0.3048	meters per second
footcandle	10.764	lux
foot-pounds of force per second	1.356	watts
gallons	3.785	liters
gallons per hour	1.052	liters per second
gallons per minute	0.0022	cubic feet per second
gallons per minute	0.06308	liters per second
grams	0.035	ounces (avoirdupois)
hectares	2.471	acres
horsepower	0.746	kilowatts
horsepower	746	watts
inches	25.4	millimeters
inches of mercury	0.033	atmospheres
inches of mercury	1.133	feet of water
inches of mercury (60°F [15.6 °C])	3377	newtons per square meter
inches of mercury	0.491	pounds per square inch
inches of water	0.002458	atmospheres
inches of water	0.036	pounds per square inch

Table A.4 Useful Conversion Factors: Alphabetized *(Continued)*

Multiply	By	To Get
inches of water (60°F) (15.6 °C)	248.8	newtons per square meter
kilocalories	3.968	British thermal units
kilocalories	4190	joules
kilograms	2.205	pounds
kilograms per cubic meter	1.686	pounds per cubic yard
kilograms per square meter	0.0033	feet of water
kilograms per square meter	0.0029	inches of mercury
kilograms per square meter	0.205	pounds per square foot
kilograms per square meter	0.001422	pounds per square inch
kilojoules	0.948	British thermal units
kilojoules per kilogram	0.430	British thermal units per pound
kilometers	0.621	miles
kilometers per hour	0.621	miles per hour
kilonewtons	0.1004	tons of force
kilonewtons	224.8	pounds of force
kilopascals	20.89	pounds of force per square foot
kilowatts	1.341	horsepower
kilowatt-hours	3.6	megajoules
liters	0.03532	cubic feet
liters	61.02	cubic inches
liters	0.2642	gallons
liters	1.057	quarts
liters per second	2.119	cubic feet per minute
liters per second	951.0	gallons per hour
liters per second	15.85	gallons per minute
megajoules	0.278	kilowatt-hours
meganewtons	100.36	tons of force
megapascals	145.04	pounds of force per square inch
megapascals	9.324	tons of force per square foot
meters	3.281	feet
meters	1094	yards
meters per second	196.86	feet per minute
meters per second	2.237	miles per hour
miles	1.609	kilometers
miles per hour	1.609	kilometers per hour
miles per hour	0.447	meters per second
milliliters	0.061	cubic inches
milliliters	0.035	fluid ounces
millimeters	0.039	inches
millimeters of mercury	133.3	newtons per square meter
million gallons per day	18.94	cubic meters per hour
newtons	0.225	pounds of force
ounces (avoirdupois)	28.35	grams
ounces (fluid)	29.6	milliliters
pounds	0.4536	kilograms

Table A.4 Useful Conversion Factors: Alphabetized *(Continued)*

Multiply	By	To Get
pounds of force	4.448	newtons
pounds of force per square foot	47.88	pascals
pounds of force per square inch	6.895	kilopascals
pounds per cubic foot	16.02	kilograms per cubic meter
pounds per cubic yard	0.593	kilograms per cubic meter
pounds per square foot	4.882	kilograms per square meter
square feet	0.0929	square meters
square inches	645.2	square millimeters
square kilometers	0.386	square miles
square meters	10.76	square feet
square meters	1.196	square yards
square miles	2.590	square kilometers
square yards	0.836	square meters
tons of force	9.964	kilonewtons
tons of force per square foot	107.25	kilopascals
tons of force per square inch	15.44	megapascals
torr (millimeters of mercury at 0°C [2 °F])	133.3	newtons per square meter
watts	3.412	British thermal units per hour
watts	0.738	foot-pounds of force per second
watts per square meter	0.317	British thermal units per square foot
yards	0.914	meters
Add your own conversion factors here.	By	To Get

[a]K or °C.

[b]Thermal conductivity (k).

[c]Thermal conductance (C) or transmittance (U).

APPENDIX B

Climatic Conditions for the United States, Canada, and Mexico

This appendix contains the following information.

Outside Design Conditions: United States and Canada (I-P units): Table B.1

Outdoor Design Conditions: Mexico and Puerto Rico: (I-P units): Table B.2

Outside Design Conditions: United States and Canada (SI units): Table B.3

Outdoor Design Conditions: Mexico and Puerto Rico: (SI units): Table B.4

Legacy Outside Design Conditions: United States and Canada (I-P units): Table B.5

Legacy Outside Design Conditions: United States and Canada (SI units): Table B.6

The climate data presented in Tables B.1 through B.4 are taken from two publications of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): the 2005 *ASHRAE Handbook—Fundamentals* (design temperatures) and ANSI/ASHRAE/IESNA Standard 90.1-2007, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (heating and cooling degree days). The information is reprinted with permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

Station Designations (where identified)
AP = airport
CO = urban areas, influenced by surroundings
AFB = Air Force base
No designation = semirural, similar to airport locations

The climate data presented in Tables B.5 and B.6 are extracted from the 10th edition of *Mechanical and Electrical Equipment for Buildings* (where they were reprinted with permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA). This "legacy" climate information is presented so that cities not available in the most recent climate data from the *ASHRAE Handbook—Fundamentals* are not "lost" for design purposes. Note that although the data presented in Tables B.5 and B.6 are similar to those presented in Tables B.1–B.4, the statistical basis of the values is different, as indicated in the column headings.

WINTER DESIGN CONDITIONS

- HDD65: Annual heating degree-days at base 65°F (18.3°C), obtained from ANSI/ASHRAE/IESNA Standard 90.1-2007. (HDD65 values are also given in Appendix C; those values may vary slightly from these values because they are based upon data from a different set of years.)
- Design dry-bulb (99%): Outdoor temperatures that will, in a normal year, be the lowest experienced during 99% of the hours in a year. This means that approximately 1% of the hours (88 hours) will experience temperatures lower than this value. These data were obtained from the 2005 *ASHRAE Handbook—Fundamentals*. Note that ASHRAE Standard 90.1 implicitly

specifies use of 99.6% values for compliant designs—and the necessary climate data reflecting these values may be obtained from that standard. The 99.6% values are more stringent than the 99% values—they represent somewhat more extreme conditions, which may be good for conservative design purposes, but will also result in larger systems and (theoretically) more energy use. The 99% values given here are believed to represent a more "green" approach to selecting design climate data.

SUMMER DESIGN CONDITIONS

- Design dry-bulb and mean coincident wet-bulb (2%): Outdoor temperatures that will, in a normal year, be the highest experienced during all but 2% of the hours in a year. This means that approximately 2% of the hours (176 hours) will experience temperatures higher than these values. *Coincident* means that the given wet-bulb temperature is likely to occur in concert with the paired dry-bulb value. These data were obtained from the 2005 *ASHRAE Handbook—Fundamentals*. Note that ASHRAE Standard 90.1 implicitly specifies use of 1% values for compliant designs—and the necessary climate data reflecting these values may be obtained from that standard. The 1% values are more stringent than the 2% values—they represent somewhat more extreme conditions, which may be good for conservative design purposes, but will also result in larger systems and (theoretically) more energy use. The 2% values given here are believed to represent a more "green" approach to selecting design climate data.
- Mean daily range: The average difference between daily maximum and minimum dry-bulb temperatures—in this case for the month of July (often used as the summer design condition for solar radiation). These data were obtained from the 2005 *ASHRAE Handbook—Fundamentals*.
- Design wet-bulb (2%): The outdoor temperature that will, in a normal year, be the highest experienced during all but 2% of the hours in a year. This value would be used for the selection and sizing of evaporative cooling components. These data were obtained from the 2005 *ASHRAE Handbook—Fundamentals*.
- CDD50: Annual cooling degree-days at base 50°F (10°C), obtained from ASHRAE Standard 90.1-2007. (CDD50 values are also given in Appendix G; they may vary slightly from these values because they are based upon data from a different set of years.)
- Other stations: Many more stations in each state or province, and for other countries, are found both in the current *ASHRAE Handbook—Fundamentals*, *ASHRAE Standard 90.1*, and at various sites on the World Wide Web.

INTERPRETATIONS BETWEEN STATIONS

As a general rule, weather data from listed stations can be adjusted for nearby locations in these ways:

- Adjustment for elevation: Elevations for many locations are given in Appendix C, Table C.19. For lower elevations, which tend to be warmer, *increase* the design temperatures:

  Dry-bulb temperature: 1F° per 200 feet of elevation (0.9C° per 100 meters of elevation)

  Wet-bulb temperature: 1F° per 500 feet of elevation (0.7C° per 200 meters of elevation)
- Adjustment for air mass (at coastlines): Along the West Coast, both dry-bulb and wet-bulb design temperatures increase with distance from the ocean. Along the Gulf Coast, dry-bulb temperatures increase for the first 200 to 300 miles (320 to 480 km) inland, while wet-bulb temperatures decrease slightly. (Beyond this 200–300-mile [320–480-km] belt, both dry-bulb and wet-bulb values decrease.)

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units)

	Winter		Summer			
State and Station[a]	**HDD65°F**	**Design Dry-Bulb (°F) (99%)**	**Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)**	**Mean Daily Range (°F)**	**Design Wet-Bulb (°F) (2%)**	**CDD50°F**
ALABAMA						
Birmingham AP	2918	23.0	90.6/74.8	18.8	76.8	5206
Huntsville AP	3323	20.5	89.7/74.1	18.4	76.3	4855
Mobile AP	1702	30.2	90.6/76.3	16.8	78.3	6761
Montgomery AP	2224	27.2	91.8/75.8	19.2	77.6	5990
Tuscaloosa	2661	24.7	91.5/75.8	19.6	77.8	5624
ALASKA						
Anchorage AP	10,570	−6.7	67.5/56.6	12.0	58.2	688
Fairbanks AP	13,940	−39.9	74.5/58.4	18.5	59.9	1040
Juneau AP	8897	7.7	66.3/56.9	13.3	58.1	559
Nome AP	14,129	−25.4	61.5/54.0	11.0	54.9	274
ARIZONA						
Flagstaff AP	7006	9.2	80.7/55.2	28.4	59.2	1661
Phoenix AP	1110	40.1	106.1/69.8	22.1	74.3	8425
Prescott AP	4995	20.5	89.3/60.1	25.8	64.5	2875
Tucson AP	1678	34.4	100.6/65.4	23.9	70.7	6921
Winslow AP	4776	15.6	91.6/59.9	28.6	63.6	3681
Yuma AP	927	44.6	106.8/72.6	23.8	77.5	8897
ARKANSAS						
Fayetteville AP	4040	14.1	90.4/74.7	20.9	76.0	4452
Fort Smith AP	3478	18.8	93.4/75.7	20.8	77.3	5078
Little Rock AP	3155	21.7	92.9/76.5	19.3	78.2	5299
Texarkana AP	2295	25.6	93.3/76.4	19.2	78.2	6152
CALIFORNIA						
Bakersfield AP	2182	35.0	98.5/69.2	26.6	70.8	6049
Burbank AP	1204	41.4	91.2/67.8	22.7	70.6	5849
Eureka AP	4496	37.5	64.4/57.9	7.3	59.1	1529
Fresno AP	2556	33.3	98.3/69.0	30.1	70.6	5350
Long Beach AP	1430	43.1	84.5/66.6	16.2	69.5	5281
Los Angeles AP	1458	46.1	77.8/64.7	10.8	67.9	4777
Oakland AP	2644	39.8	74.3/63.2	13.1	64.5	3126
Palm Springs	985	34.2	107.0/72.2	30.9	77.1	8555
Sacramento AP	2749	33.8	94.8/68.4	31.9	69.6	4474
San Diego AP	1256	46.9	78.9/67.1	8.6	70.0	5223
San Francisco AP	3016	40.0	74.1/60.9	15.6	62.3	2883
San Luis Obispo	2498	36.4	81.1/63.0	20.6	64.7	3492
Santa Barbara AP	2438	36.9	77.3/63.7	16.0	66.4	3449
Santa Maria AP	2984	34.6	76.7/≈63	18.2	≈64	2918
Stockton AP	2707	32.6	94.6/68.1	30.9	69.1	4755
COLORADO						
Alamosa AP	8749	−11.2	79.6/54.4	32.2	57.4	1374
Colorado Springs AP	6415	5.0	84.5/57.9	25.4	60.8	2312

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

		Winter		*Summer*		
State and Station[a]	**HDD65°F**	**Design Dry-Bulb (°F) (99%)**	**Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)**	**Mean Daily Range (°F)**	**Design Wet-Bulb (°F) (2%)**	**CDD50°F**
Denver AP	6020	3.3	88.0/59.6	27.4	62.3	2732
Fort Collins	6368	5.2	87.4/59.9	27.1	62.6	2411
Grand Junction AP	5548	8.9	92.0/60.1	27.1	63.0	3632
Pueblo AP	5413	5.7	92.2/62.2	31.5	65.4	3358
CONNECTICUT						
Bridgeport AP	5537	14.0	81.7/70.7	13.9	73.4	2997
Hartford	6155	7.6	85.4/70.3	20.7	73.0	2768
DELAWARE						
Wilmington AP	4937	15.0	86.5/72.9	17.2	75.3	3557
DISTRICT OF COLUMBIA						
Washington National AP	4047	20.2	89.3/74.0	16.4	76.5	4391
FLORIDA						
Daytona Beach AP	909	37.8	88.9/76.9	15.9	78.3	7567
Fort Myers AP	418	45.2	91.3/77.1	17.1	79.3	8924
Gainesville AP	1267	33.3	90.6/76.2	18.4	78.2	7009
Jacksonville AP	1434	31.8	90.9/77.0	18.3	78.5	6847
Key West AP	100	57.7	88.8/78.8	8.2	79.9	10,174
Miami AP	200	50.5	89.4/77.3	12.0	78.7	9474
Orlando AP	686	41.7	91.2/76.1	17.1	78.2	8227
Panama City, Tyndall AFB	1216	36.0	88.4/78.2	12.3	80.2	7023
Pensacola AP	1617	32.9	90.2/77.2	15.1	79.3	6816
Tallahassee AP	1705	28.3	91.7/75.9	19.1	78.3	6639
Tampa AP	725	40.6	90.3/77.4	14.6	79.2	8239
West Palm Beach AP	323	47.3	89.1/77.5	13.4	78.6	9049
GEORGIA						
Athens	2893	25.0	90.1/74.2	18.8	76.0	5079
Atlanta AP	2991	24.5	89.8/73.9	18.8	75.6	5038
Augusta AP	2565	24.8	92.2/75.3	20.8	77.2	5519
Columbus, Lawson AFB	2261	26.4	92.3/75.2	20.8	77.7	6052
Macon AP	2334	26.9	92.1/75.3	19.6	77.3	5826
Rome AP	≈3136	21.6	90.7/73.9	21.0	76.1	na
Savannah-Travis AP	1847	29.8	91.2/76.2	17.6	78.0	6389
Valdosta-Moody AFB	1552	30.4	91.8/76.2	19.6	78.4	7216
HAWAII						
Hilo AP	0	62.7	83.6/73.6	12.2	75.3	8759
Honolulu AP	0	62.8	87.8/73.1	12.6	75.1	9949
IDAHO						
Boise AP	5861	9.1	91.1/61.8	30.2	63.2	2807
Coeur D'Alene	6239	10.3	83.8/60.0	27.7	61.9	2216
Lewiston AP	5270	16.6	90.2/63.2	26.5	64.3	2964
Pocatello AP	7180	0.2	87.8/59.8	32.8	61.6	2142
ILLINOIS						
Champaign	5689	3.0	87.9/74.6	19.5	76.6	3697

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

	Winter			*Summer*		
State and Station[a]	HDD65°F	Design Dry-Bulb (°F) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)	Mean Daily Range (°F)	Design Wet-Bulb (°F) (2%)	CDD50°F
Chicago, O'Hare AP	6536	0.8	85.9/71.8	19.2	74.3	2941
Chicago CO	5753	3.1	86.6/72.1	16.0	74.7	3391
Moline AP	6474	–2.0	87.4/73.2	20.0	75.5	3207
Peoria AP	6148	0.1	86.8/73.6	19.3	75.8	3339
Rockford	6969	–3.6	85.4/71.7	19.7	74.3	2852
Springfield AP	5688	2.6	88.1/74.3	19.2	76.5	3635
INDIANA						
Evansville AP	4708	9.9	89.6/74.8	19.3	76.9	4074
Fort Wayne AP	6273	1.9	85.5/71.4	20.0	74.3	3077
Indianapolis AP	5615	4.1	86.4/73.2	18.8	75.6	3453
Lafayette	6228	3.1	87.6/73.2	20.4	75.7	3069
South Bend AP	6331	3.5	85.1/71.3	18.8	74.0	2920
Terre Haute AP	5581	5.1	87.9/74.7	19.7	76.7	3490
IOWA						
Burlington AP	5943	0.2	87.9/74.1	18.5	76.2	3601
Des Moines AP	6497	–2.9	87.4/73.3	18.3	75.3	3371
Dubuque	7327	–3.6	83.5/71.2	18.2	74.0	2672
Mason City AP	7837	–9.7	85.3/74	20.7	74.2	2653
Sioux City AP	6893	–5.3	87.6/72.7	20.4	75.0	3149
Waterloo	7406	–8.3	85.8/72.0	20.0	74.4	2813
KANSAS						
Dodge City AP	5001	6.2	94.5/69.8	24.9	71.9	4090
Goodland AP	5974	2.9	90.9/65.9	26.6	68.4	3018
Manhattan, Fort Riley	5043	6.0	93.2/74.3	22.7	75.8	4155
Topeka AP	5265	4.4	90.9/75.0	20.3	76.7	3880
Wichita AP	4791	8.7	94.5/72.8	22.2	74.8	4351
KENTUCKY						
Bowling Green AP	4328	13.9	88.8/74.5	19.5	76.3	4132
Lexington AP	4783	10.6	86.6/72.9	18.3	74.9	3754
Louisville AP	4514	13.1	88.6/74.0	18.5	76.1	4000
LOUISIANA						
Alexandria AP	2003	29.6	92.3/77.3	18.5	79.1	6407
Baton Rouge AP	1669	30.6	91.2/77.0	16.9	78.8	6845
Lafayette AP	1587	32.1	91.2/77.5	16.2	79.4	6877
Lake Charles AP	1616	32.6	90.5/77.8	15.4	79.7	6813
Monroe AP	2407	27.0	92.9/77.5	19.1	79.6	6039
New Orleans	1513	34.4	90.6/77.9	15.4	79.7	6910
Shreveport AP	2264	26.7	93.0/76.6	19.3	78.2	6166
MAINE						
Bangor, Dow AFB	7930	–1.9	81.3/67.0	20.5	69.4	1916
Caribou AP	9651	–11.3	78.2/na	19.8	na	1470
Portland	7378	3.2	80.2/67.9	18.3	70.1	1943

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

	Winter			Summer		
State and Station[a]	HDD65°F	Design Dry-Bulb (°F) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)	Mean Daily Range (°F)	Design Wet-Bulb (°F) (2%)	CDD50°F
MARYLAND						
Baltimore AP	4707	16.7	88.2/73.1	18.7	75.6	3709
Salisbury	4027	18.3	88.0/75.0	19.0	77.0	4002
MASSACHUSETTS						
Boston AP	5641	12.3	84.4/70.3	15.4	72.7	2897
Worcester AP	6979	5.9	80.0/68.4	16.2	70.8	2203
MICHIGAN						
Alpena AP	8284	−1.0	81.1/67.5	23.0	69.9	1779
Detroit	6167	8.4	85.8/70.9	17.6	73.4	3046
Escanaba	8593	−2.9	76.2/66.5	17.1	68.3	1664
Flint AP	6979	3.0	83.3/69.9	20.6	72.4	2451
Grand Rapids AP	6973	5.2	83.6/70.2	20.2	72.9	2537
Muskegon AP	6924	7.4	80.9/69.2	18.1	71.7	2361
Sault Ste. Marie AP	9316	−6.8	77.2/66.1	21.5	68.2	1421
Traverse City AP	7749	3.3	82.4/68.3	21.2	71.0	2127
MINNESOTA						
Bemidji AP	10,200	−17.8	80.8/66.0	18.8	68.1	1781
Duluth AP	9818	−15.1	77.9/65.1	19.5	67.6	1536
International Falls AP	10,487	−22.4	80.1/65.9	21.8	68.2	1630
Minneapolis/St. Paul AP	7981	−9.4	85.0/70.1	18.6	72.7	2680
Rochester AP	8250	−11.1	82.6/70.1	19.5	72.5	2376
MISSISSIPPI						
Columbus AFB	2769	25.0	92.4/76.0	19.4	78.0	5565
Jackson AP	2467	25.1	92.1/76.3	19.4	78.1	5900
Meridian AP	2444	25.2	91.9/75.9	20.4	77.8	5804
MISSOURI						
Columbia AP	5212	45.4	89.1/74.6	20.0	76.2	3752
Joplin	4303	11.6	91.2/75.0	19.5	76.6	4417
Kansas City AP	5393	3.5	89.9/74.7	19.0	76.4	3852
St. Louis AP	4758	8.0	90.5/75.0	17.8	77.0	4283
MONTANA						
Billings AP	7164	−6.6	87.2/61.4	25.9	63.0	2466
Bozeman	9908	−10.6	84.3/59.6	32.3	61.1	672
Cut Bank AP	8904	−15.1	80.2/57.3	25.4	58.8	1475
Glasgow AP	8745	−16.8	86.5/62.4	25.3	64.4	2244
Great Falls AP	7741	−12.2	84.6/59.4	27.6	60.9	1993
Helena AP	8031	−9.8	84.3/59.2	28.2	60.7	1922
Kalispell AP	8378	−2.7	82.3/60.4	29.5	61.7	1345
Lewistown AP	8479	−11.1	81.8/59.1	27.5	60.6	1580
Miles City AP	7796	−11.7	90.9/64.4	26.5	66.3	2680
Missoula AP	7792	−0.2	84.8/60.4	30.7	61.9	1679

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

		Winter			*Summer*	
State and Station[a]	HDD65°F	Design Dry-Bulb (°F) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)	Mean Daily Range (°F)	Design Wet-Bulb (°F) (2%)	CDD50°F
NEBRASKA						
Grand Island AP	6421	–1.8	89.8/71.4	22.0	73.5	3243
Lincoln CO	6278	–0.2	90.6/73.8	21.5	75.5	3455
North Platte AP	6859	–2.8	89.1/68.7	25.8	70.9	2737
Omaha AP	6300	–1.5	88.6/73.8	19.8	76.0	3398
Scottsbluff AP	6729	–2.7	89.6/64.4	29.0	66.5	2680
NEVADA						
Elko AP	7077	2.4	89.8/58.1	39.1	59.7	2144
Ely AP	7621	0.6	85.6/55.4	35.6	57.7	1717
Las Vegas AP	2407	32.1	103.7/65.5	24.5	69.1	6745
Lovelock AP	5869	9.8	93.1/59.5	35.5	61.4	2886
Reno AP	5674	14.9	89.9/58.9	35.5	60.3	2504
Tonopah AP	5733	13.7	90.2/57.2	32.0	59.8	2840
Winnemucca AP	6315	7.7	92.3/59.6	37.9	61.0	2379
NEW HAMPSHIRE						
Concord AP	7554	–1.0	84.0/68.7	23.5	71.3	2087
Portsmouth, Pease AFB	6572	8.4	82.6/69.3	18.4	71.6	2418
NEW JERSEY						
Atlantic City CO	5169	13.6	85.9/72.6	18.3	75.1	3198
Newark AP	4888	14.8	87.6/71.9	15.9	74.8	3748
NEW MEXICO						
Albuquerque AP	4425	19.9	91.0/59.9	25.3	63.7	3908
Farmington AP	5464	12.4	89.9/59.9	28.7	63.2	3307
Gallup	6244	5.1	86.3/56.9	32.0	60.5	2355
Taos	na	4.9	82.1/54.5	31.9	57.1	na
Roswell AP	3267	20.2	95.0/65.1	25.4	67.7	4962
Tucumcari AP	3912	15.7	93.0/64.4	24.5	67.7	4196
NEW YORK						
Albany AP	6894	2.2	83.0/69.9	20.6	72.2	2525
Binghamton AP	7273	3.3	79.8/67.2	17.4	69.5	2193
Buffalo AP	6747	6.2	81.3/68.3	17.1	71.1	2468
Massena AP	8255	–9.2	82.2/69.1	21.5	71.3	2046
NYC, Kennedy AP	5027	17.5	83.5/71.2	13.4	74.6	3342
Rochester AP	6734	5.6	82.9/69.8	19.7	72.1	2406
Syracuse AP	6834	2.9	83.0/69.8	19.7	72.0	2399
NORTH CAROLINA						
Asheville AP	4308	16.9	83.7/70.6	19.4	72.4	3365
Charlotte AP	3341	22.5	89.2/73.5	18.0	75.2	4704
Greensboro AP	3865	19.7	87.7/73.1	18.2	74.9	4144
Raleigh/Durham AP	3457	21.2	89.0/74.4	19.1	76.2	4499
Wilmington AP	2470	26.9	89.1/77.0	15.8	78.4	5557

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

	Winter		Summer			
State and Station[a]	HDD65°F	Design Dry-Bulb (°F) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)	Mean Daily Range (°F)	Design Wet-Bulb (°F) (2%)	CDD50°F
NORTH DAKOTA						
Bismarck AP	8968	−15.2	86.2/66.7	25.9	69.2	2144
Fargo AP	9254	−16.5	84.8/68.5	21.6	71.1	2289
Minot AP	9193	−15.4	84.2/65.5	22.1	68.3	2135
OHIO						
Akron-Canton AP	6160	5.5	82.9/70.0	18.5	72.3	2779
Cincinnati CO	4988	11.7	88.0/73.1	19.9	75.4	3733
Cleveland AP	6201	6.1	83.7/70.9	18.2	73.1	2755
Columbus AP	5708	9.8	87.2/73.4	19.7	75.4	3119
Dayton AP	5708	5.1	85.7/71.7	19.2	74.0	3249
Mansfield AP	6258	4.1	82.8/70.5	18.3	73.0	2818
Toledo AP	6579	3.4	85.1/71.2	20.7	73.7	2720
Youngstown AP	6544	5.2	82.9/69.4	20.7	71.9	2536
OKLAHOMA						
Oklahoma City AP	3659	17.4	94.5/73.8	19.9	75.5	4972
Tulsa AP	3691	14.7	94.5/75.7	19.1	77.4	5150
OREGON						
Astoria AP	5158	29.3	69.0/60.9	13.1	61.9	1437
Eugene AP	4546	25.6	83.5/64.4	27.9	65.5	2354
Medford AP	4611	24.7	91.6/64.5	32.9	65.7	2989
Pendleton AP	5294	11.2	89.2/62.2	27.3	63.4	2787
Portland AP	4522	27.0	83.1/65.0	21.2	65.9	2517
Salem AP	4927	24.9	83.6/64.5	27.0	65.3	2100
PENNSYLVANIA						
Allentown AP	5785	11.1	85.4/70.9	19.1	73.3	3028
Erie AP	6279	7.7	80.9/70.2	15.2	72.1	2652
Harrisburg AP	5347	13.2	87.0/71.2	20.1	73.7	3358
Philadelphia AP	4954	15.8	87.6/73.0	17.1	75.7	3623
Pittsburgh AP	5968	10.0	84.6/69.8	17.9	72.4	2836
Williamsport	6087	8.3	84.2/70.1	20.1	72.8	2796
RHODE ISLAND						
Providence AP	5884	10.8	83.6/70.3	17.4	73.2	2743
SOUTH CAROLINA						
Anderson	2965	25.4	90.6/74.0	20.1	76.0	4900
Charleston CO	1866	29.1	90.1/76.9	16.1	78.5	6303
Columbia AP	2649	24.6	92.0/74.6	20.1	76.7	5508
Greenville AP	3272	23.6	88.7/73.2	18.6	75.0	4625
SOUTH DAKOTA						
Huron AP	7923	−11.1	87.8/70.8	23.0	73.2	2709
Pierre AP	7411	−7.8	91.2/69.0	25.3	71.5	2938
Rapid City AP	7301	−5.3	87.9/64.7	25.4	67.4	2412
Sioux Falls AP	7809	−10.1	87.0/71.0	21.3	73.4	2735

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

	Winter			*Summer*		
State and Station[a]	**HDD65°F**	**Design Dry-Bulb (°F) (99%)**	**Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)**	**Mean Daily Range (°F)**	**Design Wet-Bulb (°F) (2%)**	**CDD50°F**
TENNESSEE						
Bristol-Tri City AP	4406	14.0	84.7/71.1	19.1	72.9	3621
Chattanooga AP	3587	20.5	89.8/74.1	19.4	75.9	4609
Knoxville AP	3937	19.1	87.9/73.5	18.3	75.2	4164
Memphis AP	3082	21.4	92.2/76.7	16.8	78.4	5467
Nashville AP	3729	16.7	89.8/74.4	18.6	76.3	4689
TEXAS						
Abilene AP	2584	22.1	95.1/70.7	20.8	73.4	6050
Amarillo AP	4258	12.4	92.0/66.4	24.1	69.1	4128
Austin AP	1688	29.8	94.9/74.7	19.9	77.1	7171
Brownsville AP	635	39.9	93.1/77.5	16.4	79.4	8777
Corpus Christi AP	1016	36.4	92.7/77.8	17.2	79.8	8023
Dallas AP	2259	25.0	96.2/74.8	20.1	77.1	6587
Del Rio, Laughlin AFB	1565	33.6	99.4/72.6	21.4	76.3	7207
El Paso AP	2708	25.8	96.1/64.1	24.2	68.5	5488
Fort Worth AP	2304	25.0	97.0/74.8	19.9	77.0	6557
Galveston	1263	38.7	88.5/78.6	7.4	80.2	7378
Houston/Hobby	1371	35.1	92.0/77.3	16.3	79.3	7357
Laredo AFB	1025	37.1	99.0/73.3	21.3	77.0	8495
Lubbock AP	3431	18.0	93.4/67.4	22.3	70.7	4833
Lufkin AP	1951	28.1	92.8/76.6	19.9	78.4	6527
Midland AP	2751	22.9	95.5/67.5	23.8	71.1	5588
Port Arthur AP	1499	33.0	91.0/78.5	15.8	80.2	6994
San Angelo AP	2414	24.4	95.5/70.3	22.4	73.2	6070
San Antonio AP	1644	30.7	94.5/73.8	18.5	76.8	7142
Waco AP	2179	26.6	96.9/75.4	21.2	77.4	6668
Wichita Falls AP	3042	19.9	97.8/73.4	23.6	75.5	5717
UTAH						
Cedar City AP	5962	9.0	88.9/58.2	29.3	61.1	2770
Salt Lake City	5765	12.8	92.1/61.5	26.6	64.2	3276
VERMONT						
Burlington AP	7066	–4.4	82.2/68.2	19.7	70.7	2228
Rutland	7771	–1.2	79.8/66.7	19.0	68.8	2345
VIRGINIA						
Norfolk AP	3495	24.4	88.8/74.9	15.2	76.9	4478
Richmond AP	3963	19.3	89.6/74.5	19.0	76.6	4223
Roanoke AP	4360	17.3	87.1/71.5	19.4	73.4	3715
WASHINGTON						
Bellingham AP	5609	22.4	73.0/62.2	15.2	63.0	1508
Olympia AP	5655	23.2	79.3/63.5	24.3	64.2	1558
Seattle CO	4611	28.1	79.2/62.9	18.0	63.9	2120
Seattle–Tacoma AP	4908	28.4	77.6/62.3	18.5	63.1	2021
Spokane AP	6842	12.0	87.9/63.1	28.3	64.4	2032

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

		Winter			*Summer*	
State and Station[a]	**HDD65°F**	**Design Dry-Bulb (°F) (99%)**	**Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)**	**Mean Daily Range (°F)**	**Design Wet-Bulb (°F) (2%)**	**CDD50°F**
Walla Walla AP	4958	14.6	91.2/64.3	27.2	65.5	3161
Yakima AP	5967	10.7	88.5/63.5	31.3	64.7	2348
WEST VIRGINIA						
Beckley	5558	11.0	80.6/68.2	17.3	70.2	2690
Charleston AP	4646	12.4	86.1/72.0	19.0	74.1	3655
Huntington CO	4665	12.5	86.7/72.6	19.0	74.9	3615
Morgantown	5363	11.2	84.5/70.3	19.8	72.8	3155
WISCONSIN						
Eau Claire AP	8330	−11.6	84.1/69.5	20.3	72.2	2407
Green Bay AP	8089	−6.0	82.3/70.1	20.2	72.3	2177
La Cross AP	7491	−7.3	85.7/71.6	20.0	74.3	2790
Madison AP	7673	−4.8	84.2/70.7	21.1	72.8	2389
Milwaukee AP	7324	0.1	83.2/70.7	16.1	73.0	2388
WYOMING						
Casper AP	7682	−4.3	87.3/58.1	31.4	60.5	2082
Cheyenne AP	7326	0.7	82.6/57.1	25.7	60.1	1886
Lander AP	7889	−6.2	85.5/57.2	27.3	59.3	2184
Laramie AP	9008	−2.7	79.1/53.4	29.2	56.1	1237
Rock Springs AP	8365	0.3	81.9/53.4	27.2	55.4	1734
Sheridan AP	7804	−7.8	87.2/61.7	29.7	63.7	2023
ALBERTA						
Calgary AP	9885	−15.1	76.2/57.6	21.9	59.1	1167
Edmonton AP	11,023	−21.3	74.8/60.4	21.1	61.9	1069
Medicine Hat AP	8988	−18.3	83.5/61.8	24.6	62.4	1981
BRITISH COLUMBIA						
Prince George AP	9495	−16.9	74.1/57.7	22.0	59.0	906
Prince Rupert CO	7650	15.2	61.5/56.2	9.1	57.3	572
Vancouver AP	5682	23.9	71.5/62.4	13.7	63.2	1536
Victoria CO	5494	26.7	72.5/60.7	18.0	61.3	1286
MANITOBA						
The Pas	12,490	−27.1	76.5/62.3	18.6	64.3	1231
Winnipeg AP	10,858	−22.3	80.8/66.1	20.6	68.1	1784
NEW BRUNSWICK						
Fredericton AP	8666	−6.3	79.6/65.9	20.4	68.2	1631
Saint John AP	8776	−3.7	73.0/62.1	17.2	64.2	1179
NEWFOUNDLAND						
Gander	9354	−0.2	72.7/62.0	17.6	64.0	1075
St. John’s AP	8888	6.6	70.4/62.7	15.8	64.4	848
NORTHWEST TERR.						
Fort Smith AP	14,192	−36.2	75.8/59.8	20.9	61.6	932
Inuvik	18,409	−43.1	71.3/57.2	18.1	58.2	489
Yellowknife AP	15,555	−39.0	71.2/57.6	14.3	59.1	851

Table B.1 Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

	Winter			Summer		
State and Station[a]	HDD65°F	Design Dry-Bulb (°F) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)	Mean Daily Range (°F)	Design Wet-Bulb (°F) (2%)	CDD50°F
NOVA SCOTIA						
Halifax AP	8133	2.3	75.5/64.6	16.6	67.0	1464
Sydney AP	8364	3.2	74.7/64.8	17.1	66.6	1287
Yarmouth AP	7515	10.4	69.1/63.5	13.1	64.7	1180
ONTARIO						
Ottawa AP	8571	−7.3	80.6/67.1	18.2	69.5	2045
Sudbury AP	9990	−13.7	78.0/64.1	18.9	66.7	1557
Thunder Bay	10,562	−17.1	76.9/64.3	21.7	66.0	1198
Toronto AP	7306	2.0	81.2/68.2	19.1	70.4	2370
PRINCE EDWARD ISLAND						
Charlottetown AP	8598	−1.4	74.7/65.4	15.1	67.2	1400
QUEBEC						
Montréal AP	8285	−6.6	80.1/68.2	17.1	70.2	2146
Québec AP	9449	−11.0	78.0/66.2	18.4	68.5	1571
Sept Iles AP	11,287	−15.1	67.0/58.6	13.4	60.3	690
Trois Rivières	9124	−9.1	76.3/68.4	12.0	69.9	1766
Val d'Or AP	11,256	−22.6	77.0/63.4	20.2	65.7	1193
SASKATCHEWAN						
Prince Albert AP	12,009	−29.6	77.5/61.6	21.1	63.5	1252
Regina AP	10,773	−24.1	81.1/62.5	22.9	64.5	1620
Saskatoon AP	11,118	−26.0	79.7/61.9	22.4	63.7	1537
YUKON TERRITORY						
Whitehorse AP	12,797	−35.2	69.7/54.0	20.9	55.1	611

[a]U.S. solar data are available from the National Climatic Data Center, Federal Building, Asheville, NC 28801. Canadian solar data are available from The Canadian Climate Center, Atmospheric Environment Service, 4905 Dufferin St., Downsview, Ontario M3H 5T4.

Table B.2 Outdoor Design Conditions: Mexico and Puerto Rico (I-P units)

	Winter			Summer		
Country and Station	HDD65°F	Design Dry-Bulb (°F) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°F) (2%)	Mean Daily Range (°F)	Design Wet-Bulb (°F) (2%)	CDD50°F
MEXICO						
Guadalajara	701	38.8	88.2/60.1	18.6	67.0	—
Mérida	10	60.4	96.6/75.7	19.5	79.7	11,112
Mexico City	1203	42.4	80.4/56.4	18.8	60.2	4762
Monterrey	844	41.3	98.4/74.5	21.8	77.8	8326
PUERTO RICO						
San Juan	0	70.5	89.2/77.8	10.4	79.7	11,406

Table B.3 Outdoor Design Conditions: United States and Canada (SI units)

	Winter		Summer			
State and Station[a]	HDD18.3°C	Design Dry-Bulb (°C) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2%)	CDD10.0°C
ALABAMA						
Birmingham AP	1621	−5.0	32.5/23.8	10.4	24.9	2892
Huntsville AP	1846	−6.4	32.1/23.4	10.2	24.6	2697
Mobile AP	946	−1.0	32.6/24.6	9.3	25.7	3756
Montgomery AP	1236	−2.7	33.2/24.3	10.7	25.3	3328
Tuscaloosa	1478	−4.1	33.1/24.3	10.9	25.4	3124
ALASKA						
Anchorage AP	5872	−21.5	19.7/13.7	6.7	14.6	382
Fairbanks AP	7744	−40.0	23.6/14.7	10.3	15.5	578
Juneau AP	4943	−13.5	19.1/13.8	7.4	14.5	311
Nome AP	7849	−31.9	16.4/12.2	6.1	12.7	152
ARIZONA						
Flagstaff AP	3892	−12.7	27.1/12.9	15.8	15.1	923
Phoenix AP	617	4.5	41.2/21.0	12.3	23.5	4680
Prescott AP	2775	−6.4	31.8/15.6	14.3	18.1	1597
Tucson AP	932	1.3	38.1/18.6	13.3	21.5	3845
Winslow AP	2653	−9.1	33.1/15.5	15.9	17.6	2045
Yuma AP	515	7.0	41.6/22.6	13.2	25.3	4943
ARKANSAS						
Fayetteville AP	2244	−9.9	32.4/23.7	11.6	24.4	2473
Fort Smith AP	1932	−7.3	34.1/24.3	11.6	25.2	2821
Little Rock AP	1753	−5.7	33.8/24.7	10.7	25.7	2944
Texarkana AP	1275	−3.6	34.1/24.7	10.7	25.7	3418
CALIFORNIA						
Bakersfield AP	1212	1.7	36.9/20.7	14.8	21.6	3361
Burbank AP	669	5.2	32.9/19.9	12.6	21.4	3249
Eureka AP	2498	3.1	18.0/14.4	4.1	15.1	849
Fresno AP	1420	0.7	36.8/20.6	16.7	21.4	2972
Long Beach AP	794	6.2	29.2/19.2	9.0	20.8	2934
Los Angeles AP	810	7.8	25.4/18.2	6.0	19.9	2654
Oakland AP	1469	4.3	23.5/17.3	7.3	18.1	1737
Palm Springs	547	1.2	41.7/22.3	17.2	25.1	4753
Sacramento AP	1527	1.0	34.9/20.2	17.7	20.9	2486
San Diego AP	698	8.3	26.1/19.5	4.8	21.1	2902
San Francisco AP	1676	4.4	23.4/16.1	8.7	16.8	1602
San Luis Obispo	1388	2.4	27.3/17.2	11.4	18.2	1940
Santa Barbara AP	1354	2.7	25.2/17.6	8.9	19.1	1916
Santa Maria AP	1658	1.4	24.8/≈17	10.1	≈18	1621
Stockton AP	1504	0.3	34.8/20.1	17.2	20.6	2642
COLORADO						
Alamosa AP	4861	−24.0	26.4/12.4	17.9	12.6	763
Colorado Springs AP	3564	−15.0	29.2/14.4	14.1	16.0	1284
Denver AP	3344	−15.9	31.1/15.3	15.2	16.8	1517

Table B.3 Outdoor Design Conditions: United States and Canada (SI units) *(Continued)*

	Winter		Summer			
State and Station[a]	HDD18.3°C	Design Dry-Bulb (°C) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2%)	CDD10.0°C
Fort Collins	3538	−14.9	30.8/15.5	15.1	17.0	1339
Grand Junction AP	3082	−12.8	33.3/15.6	15.1	17.2	2018
Pueblo AP	3007	−14.6	33.4/16.8	17.5	18.6	1866
CONNECTICUT						
Bridgeport AP	3076	−10.0	27.6/21.5	7.7	23.0	1665
Hartford	3419	−13.6	29.7/21.3	11.5	22.8	1538
DELAWARE						
Wilmington AP	2743	−9.4	30.3/22.7	9.6	24.1	1976
DISTRICT OF COLUMBIA						
Washington National AP	2248	−6.6	31.8/23.3	9.1	24.7	2439
FLORIDA						
Daytona Beach AP	505	3.2	31.6/24.9	8.8	25.7	4204
Fort Myers AP	232	7.3	32.9/25.1	9.5	26.3	4958
Gainesville AP	704	0.7	32.6/24.6	10.2	25.7	3894
Jacksonville AP	797	−0.1	32.7/25.0	4.6	25.8	3804
Key West AP	56	14.3	31.6/26.0	4.6	26.6	5652
Miami AP	111	10.3	31.9/25.2	6.7	25.9	5263
Orlando AP	381	5.4	32.9/24.5	9.5	25.7	4571
Panama City, Tyndall AFB	676	2.2	31.3/25.7	6.8	26.8	3902
Pensacola AP	898	0.5	32.3/25.1	8.4	26.3	3787
Tallahassee AP	947	−2.1	33.2/24.4	10.6	25.7	3688
Tampa AP	403	4.8	32.4/25.2	8.1	26.2	4577
West Palm Beach AP	179	8.5	31.7/25.3	7.4	25.9	5027
GEORGIA						
Athens	1607	−3.9	32.3/23.4	10.4	24.4	2822
Atlanta AP	1662	−4.2	32.1/23.3	10.4	24.2	2799
Augusta AP	1425	−4.0	33.4/24.1	11.6	25.1	3066
Columbus, Lawson AFB	1256	−3.1	33.5/24.0	11.6	25.4	3362
Macon AP	1297	−2.8	33.4/24.1	10.9	25.2	3237
Rome AP	≈1742	−5.8	32.6/23.3	11.7	24.5	na
Savannah-Travis AP	1026	−1.2	32.9/24.6	9.8	25.6	3549
Valdosta-Moody AFB	862	−0.9	33.2/24.6	10.9	25.8	4009
HAWAII						
Hilo AP	0	17.1	28.7/23.1	6.8	24.1	4866
Honolulu AP	0	17.1	31.0/22.8	7.0	23.9	5527
IDAHO						
Boise AP	3256	−12.7	32.8/16.6	16.8	17.3	1559
Coeur D'Alene	3466	−12.1	28.8/15.6	15.4	16.6	1231
Lewiston AP	2928	−8.6	32.3/17.3	14.7	17.9	1647
Pocatello AP	3989	−17.7	31.0/15.4	18.2	16.4	1190
ILLINOIS						
Champaign	3161	−16.1	31.1/23.7	10.8	24.8	2054
Chicago, O'Hare AP	3631	−17.3	29.9/22.1	10.7	23.5	1634
Chicago CO	3196	−16.1	30.3/22.3	8.9	23.7	1884

Table B.3 Outdoor Design Conditions: United States and Canada (SI units) *(Continued)*

	Winter		*Summer*			
State and Station[a]	HDD18.3°C	Design Dry-Bulb (°C) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2%)	CDD10.0°C
Moline AP	3597	−18.9	30.8/22.9	11.1	24.2	1782
Peoria AP	3416	−17.7	30.4/23.1	10.7	24.3	1855
Rockford	3872	−19.8	29.7/22.1	10.9	23.5	1584
Springfield AP	3160	−16.3	31.2/23.5	10.7	24.7	2019
INDIANA						
Evansville AP	2616	−12.3	32.0/21.9	10.7	24.9	2263
Fort Wayne AP	3485	−16.7	29.7/21.9	11.1	23.5	1709
Indianapolis AP	3119	−15.5	30.2/22.9	10.4	24.2	1918
Lafayette	3460	−16.1	30.9/22.9	11.3	24.3	1705
South Bend AP	3517	−15.8	29.5/21.8	10.4	23.3	1622
Terre Haute AP	3101	−14.9	31.1/23.7	10.9	24.8	1939
IOWA						
Burlington AP	3302	−17.7	31.1/23.4	10.3	24.6	2001
Des Moines AP	3609	−19.4	30.8/22.9	10.2	24.1	1837
Dubuque	4071	−19.7	28.6/21.8	10.1	23.3	1484
Mason City AP	4354	−23.2	29.6/23.3	11.5	23.4	1474
Sioux City AP	3829	−20.7	30.9/22.6	11.3	23.9	1749
Waterloo	4114	−22.4	29.9/22.2	11.1	23.6	1563
KANSAS						
Dodge City AP	2778	−14.3	34.7/21.0	13.8	22.2	2272
Goodland AP	3319	−16.2	32.7/18.8	14.8	20.2	1677
Manhattan, Fort Riley	2802	−14.4	34.0/23.5	12.6	24.3	2308
Topeka AP	2925	−15.3	32.7/23.9	11.3	24.8	2156
Wichita AP	2662	−12.9	34.7/22.7	12.3	23.8	2417
KENTUCKY						
Bowling Green AP	2404	−10.1	31.6/23.6	10.8	24.6	2296
Lexington AP	2657	−11.9	30.3/22.7	10.2	23.8	2086
Louisville AP	2508	−10.5	31.4/23.3	10.3	24.5	2222
LOUISIANA						
Alexandria AP	1113	−1.3	33.5/25.2	10.3	26.2	3559
Baton Rouge AP	927	−0.8	32.9/25.0	9.4	26.0	3803
Lafayette AP	882	0.1	32.9/25.3	9.0	26.3	3821
Lake Charles AP	898	0.3	32.5/25.4	8.6	26.5	3785
Monroe AP	1337	−2.8	33.8/25.3	10.6	26.4	3355
New Orleans	841	1.3	32.6/25.5	8.6	26.5	3839
Shreveport AP	1258	−2.9	33.9/24.8	10.7	25.7	3426
MAINE						
Bangor, Dow AFB	4406	−18.8	27.4/19.4	11.4	20.8	1064
Caribou AP	5362	−24.1	25.7/na	11.0	na	817
Portland	4099	−16.0	26.8/19.9	10.2	21.2	1079
MARYLAND						
Baltimore AP	2615	−8.5	31.2/22.8	10.4	24.2	2061

Table B.3 Outdoor Design Conditions: United States and Canada (SI units) *(Continued)*

	Winter		Summer			
State and Station[a]	**HDD18.3°C**	**Design Dry-Bulb (°C) (99%)**	**Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)**	**Mean Daily Range (°C)**	**Design Wet-Bulb (°C) (2%)**	**CDD10.0°C**
Salisbury	2237	−7.6	31.1/23.9	10.6	25.0	2223
MASSACHUSETTS						
Boston AP	3134	−10.9	29.1/21.3	8.5	22.6	1609
Worcester AP	3877	−14.5	26.7/20.2	9.0	21.6	1224
MICHIGAN						
Alpena AP	4602	−18.3	27.3/19.7	12.8	21.1	988
Detroit	3426	−13.1	29.9/21.6	9.8	23.0	1692
Escanaba	4774	−19.4	24.6/19.2	9.5	20.2	924
Flint AP	3877	−16.1	28.5/21.1	11.4	22.4	1362
Grand Rapids AP	3874	−14.9	28.7/21.2	11.2	22.7	1409
Muskegon AP	3847	−13.7	27.2/20.7	10.1	22.1	1312
Sault Ste. Marie AP	5176	−21.6	25.1/18.9	11.9	20.1	789
Traverse City AP	4305	−15.9	28.0/20.2	11.8	21.7	1182
MINNESOTA						
Bemidji AP	5667	−27.7	27.1/18.9	10.4	20.1	989
Duluth AP	5454	−26.2	25.5/18.4	10.8	19.8	853
International Falls AP	5826	−30.2	26.7/18.8	12.1	20.1	906
Minneapolis/St. Paul AP	4434	−23.0	29.4/21.2	10.3	22.6	1489
Rochester AP	4583	−23.9	28.1/21.2	10.8	22.5	1320
MISSISSIPPI						
Columbus AFB	1538	−3.9	33.6/24.4	10.7	25.6	3092
Jackson AP	1371	−3.8	33.6/24.6	10.7	25.6	3278
Meridian AP	1358	−3.8	33.3/24.4	11.3	25.4	3224
MISSOURI						
Columbia AP	2896	7.4	31.7/23.7	11.1	24.6	2084
Joplin	2391	−11.3	32.9/23.9	10.8	24.8	2454
Kansas City AP	2996	−15.8	32.2/23.7	10.6	24.7	2140
St Louis AP	2643	−13.3	32.5/23.9	9.9	25.0	2379
MONTANA						
Billings AP	3980	−21.4	30.7/16.3	14.4	17.2	1370
Bozeman	5504	−23.7	29.1/15.3	17.9	16.2	373
Cut Bank AP	4947	−26.2	26.8/14.1	14.1	14.9	819
Glasgow AP	4858	−27.1	30.3/16.9	14.1	18.0	1247
Great Falls AP	4301	−24.6	29.2/15.2	15.3	16.1	1107
Helena AP	4462	−23.2	29.1/15.1	15.7	16.9	1068
Kalispell AP	4654	−19.3	27.9/15.8	16.4	16.5	747
Lewistown AP	4711	−23.9	27.7/15.1	15.3	15.9	878
Miles City AP	4331	−24.3	32.7/18.0	14.7	19.1	1489
Missoula AP	4329	−17.9	29.3/15.8	17.1	16.6	933
NEBRASKA						
Grand Island AP	3567	−18.8	32.1/21.9	12.2	23.1	1802
Lincoln CO	3488	−17.9	32.6/23.2	11.9	24.2	1919
North Platte AP	3811	−19.3	31.7/20.4	14.3	21.6	1521

Table B.3 Outdoor Design Conditions: United States and Canada (SI units) *(Continued)*

	Winter				*Summer*	
State and Station[a]	HDD18.3°C	Design Dry-Bulb (°C) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2%)	CDD10.0°C
Omaha AP	3500	−18.6	31.4/23.2	11.0	24.4	1888
Scottsbluff AP	3738	−19.3	32.0/18.0	16.1	19.2	1489
NEVADA						
Elko AP	3932	−16.4	32.1/14.5	21.7	15.4	1191
Ely AP	4234	−17.4	29.8/13.0	19.8	14.3	954
Las Vegas AP	1337	0.1	39.8/18.6	13.6	20.6	3747
Lovelock AP	3261	−12.3	33.9/15.3	19.7	16.3	1603
Reno AP	3152	−9.5	32.2/14.9	19.7	15.7	1391
Tonopah AP	3185	−10.2	32.3/14.0	17.8	15.4	1578
Winnemucca AP	3508	−13.5	33.5/15.3	21.1	16.1	1322
NEW HAMPSHIRE						
Concord AP	4197	−18.3	28.9/20.4	13.1	21.8	1159
Portsmouth, Pease AFB	3651	−13.1	28.1/20.7	10.2	22.0	1343
NEW JERSEY						
Atlantic City CO	2872	−10.2	29.9/22.6	10.2	23.9	1777
Newark AP	2716	−9.6	30.9/22.2	8.8	23.8	2082
NEW MEXICO						
Albuquerque AP	2458	−6.7	32.8/15.5	14.1	17.6	2171
Farmington AP	3036	−10.9	32.2/15.5	15.9	17.3	1837
Gallup	3469	−14.9	30.2/13.8	17.8	15.8	1308
Taos	na	−15.1	27.8/12.5	17.7	13.9	na
Roswell AP	1815	−6.6	35.0/18.4	14.1	19.8	2757
Tucumcari AP	2173	−9.1	33.4/18.0	13.6	19.8	2331
NEW YORK						
Albany AP	3830	−16.6	28.3/21.1	11.4	22.3	1403
Binghamton AP	4041	−15.9	26.6/19.6	9.7	20.8	1218
Buffalo AP	3748	−14.3	27.4/20.2	9.5	21.7	1371
Massena AP	4586	−22.9	27.9/20.6	11.9	21.8	1137
NYC, Kennedy AP	2793	−8.1	28.6/21.8	7.4	23.7	1857
Rochester AP	3741	−14.7	28.3/21.0	10.9	22.3	1337
Syracuse AP	3797	−16.2	28.3/21.0	10.9	22.2	1333
NORTH CAROLINA						
Asheville AP	2393	−8.4	28.7/21.4	10.8	22.4	1869
Charlotte AP	1856	−5.3	31.8/23.1	10.0	24.0	2613
Greensboro AP	2147	−6.8	30.9/22.8	10.1	23.8	2302
Raleigh/Durham AP	1921	−6.0	31.7/23.6	10.6	24.6	2499
Wilmington AP	1372	−2.8	31.7/25.0	8.8	25.8	3087
NORTH DAKOTA						
Bismarck AP	4982	−26.2	30.1/19.3	14.4	20.7	1191
Fargo AP	5141	−26.9	29.3/20.3	12.0	21.7	1272
Minot AP	5107	−26.3	29.0/18.6	12.3	20.2	1186
OHIO						
Akron-Canton AP	3422	−14.7	28.3/21.1	10.3	22.4	1544

Table B.3 Outdoor Design Conditions: United States and Canada (SI units) *(Continued)*

	Winter		*Summer*			
State and Station[a]	HDD18.3°C	Design Dry-Bulb (°C) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2%)	CDD10.0°C
Cincinnati CO	2771	−11.3	31.1/22.8	11.1	24.1	2074
Cleveland AP	3445	−14.4	28.7/21.6	10.1	22.8	1531
Columbus AP	3171	−12.3	30.7/23.0	10.9	24.1	1733
Dayton AP	3171	−14.9	29.8/22.1	10.7	23.3	1805
Mansfield AP	3477	−15.5	28.2/21.4	10.2	22.8	1566
Toledo AP	3655	−15.9	29.5/21.8	11.5	23.2	1511
Youngstown AP	3636	−14.9	28.3/20.8	11.5	22.2	1409
OKLAHOMA						
Oklahoma City AP	2033	−8.1	34.7/23.2	11.1	24.2	2762
Tulsa AP	2051	−9.6	34.7/24.3	10.6	25.2	2861
OREGON						
Astoria AP	2866	−1.5	20.6/16.1	7.3	16.6	798
Eugene AP	2526	−3.6	28.6/18.0	15.5	18.6	1308
Medford AP	2562	−4.1	33.1/18.1	18.3	18.7	1661
Pendleton AP	2941	−11.6	31.8/16.8	15.2	17.4	1548
Portland AP	2512	−2.8	28.4/18.3	11.8	18.8	1398
Salem AP	2737	−3.9	28.7/18.1	15.0	18.5	1167
PENNSYLVANIA						
Allentown AP	3214	−11.6	29.7/21.6	10.6	22.9	1682
Erie AP	3488	−13.5	27.2/21.2	8.4	22.3	1473
Harrisburg AP	2971	−10.4	30.6/21.8	11.2	23.2	1866
Philadelphia AP	2752	−9.0	30.9/22.8	9.5	24.3	2013
Pittsburgh AP	3316	−12.2	29.2/21.0	9.9	22.4	1576
Williamsport	3382	−13.2	29.0/21.2	11.2	22.7	1553
RHODE ISLAND						
Providence AP	3269	−11.8	28.7/21.3	9.7	22.9	1524
SOUTH CAROLINA						
Anderson	1647	−3.7	32.6/23.3	11.2	24.4	2722
Charleston CO	1037	−1.6	32.3/24.9	8.9	25.8	3502
Columbia AP	1472	−4.1	33.3/23.7	11.2	24.8	3060
Greenville AP	1818	−4.7	31.5/22.9	10.3	23.9	2569
SOUTH DAKOTA						
Huron AP	4402	−23.9	31.0/21.6	12.8	22.9	1505
Pierre AP	4117	−22.1	32.9/20.6	14.1	21.9	1632
Rapid City AP	4056	−20.7	31.1/18.2	14.1	19.7	1340
Sioux Falls AP	4338	−23.4	30.6/21.7	11.8	23.0	1519
TENNESSEE						
Bristol-Tri City AP	2448	−10.0	29.3/21.7	10.6	22.7	2012
Chattanooga AP	1993	−6.4	32.1/23.4	10.8	24.4	2561
Knoxville AP	2187	−7.2	31.1/23.1	10.2	24.0	2313
Memphis AP	1712	−5.9	33.4/24.8	9.3	25.8	3037
Nashville AP	2072	−8.5	32.1/23.6	10.3	24.6	2605

Table B.3 Outdoor Design Conditions: United States and Canada (SI units) *(Continued)*

	Winter		Summer			
State and Station[a]	HDD18.3°C	Design Dry-Bulb (°C) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2%)	CDD10.0°C
TEXAS						
Abilene AP	1436	−5.5	35.1/21.5	11.6	23.0	3361
Amarillo AP	2366	−10.9	33.3/19.1	13.4	20.6	2293
Austin AP	938	−1.2	34.9/23.7	11.1	25.1	3984
Brownsville AP	353	4.4	33.9/25.3	9.1	26.3	4876
Corpus Christi AP	564	2.4	33.7/25.4	9.6	26.6	4457
Dallas AP	1255	−3.9	35.7/23.8	11.2	25.1	3659
Del Rio, Laughlin AFB	869	0.9	37.4/22.6	11.9	24.6	4004
El Paso AP	1504	−3.4	35.6/17.8	13.4	20.3	3049
Fort Worth AP	1280	−3.9	36.1/23.8	11.1	25.0	3643
Galveston	702	3.7	31.4/25.9	4.1	26.8	4099
Houston/Hobby	762	1.7	33.3/25.2	9.1	26.3	4087
Laredo AFB	569	2.8	37.2/22.9	11.8	25.0	4719
Lubbock AP	1906	−7.8	34.1/19.7	12.4	21.5	2685
Lufkin AP	1084	−2.2	33.8/24.8	11.1	25.8	3626
Midland AP	1528	−5.1	35.3/19.7	13.2	21.7	3104
Port Arthur AP	833	0.6	32.8/25.8	8.8	26.8	3886
San Angelo AP	1341	−4.2	35.3/21.3	12.4	22.9	3372
San Antonio AP	913	−0.7	34.7/23.2	10.3	24.9	3968
Waco AP	1211	−3.0	36.1/24.1	11.8	25.2	3704
Wichita Falls AP	1690	−6.7	36.6/23.0	13.1	24.2	3176
UTAH						
Cedar City AP	3312	−12.8	31.6/14.6	16.3	16.2	1539
Salt Lake City	3203	−10.7	33.4/16.4	14.8	17.9	1820
VERMONT						
Burlington AP	3926	−20.2	27.9/20.1	10.9	21.5	1238
Rutland	4317	−18.4	26.6/19.3	10.6	20.4	1303
VIRGINIA						
Norfolk AP	1942	−4.2	31.6/23.8	8.4	24.9	2488
Richmond AP	2202	−7.1	32.0/23.6	10.6	24.8	2346
Roanoke AP	2422	−8.2	30.6/21.9	10.8	23.0	2064
WASHINGTON						
Bellingham AP	3116	−5.3	22.8/16.8	8.4	17.2	838
Olympia AP	3142	−4.9	26.3/17.5	13.5	17.9	866
Seattle CO	2562	−2.2	26.2/17.2	10.0	17.7	1178
Seattle–Tacoma AP	2727	−2	25.3/16.8	10.3	17.3	1123
Spokane AP	3801	−11.1	31.1/17.3	15.7	18.0	1129
Walla Walla AP	2754	−9.7	32.9/17.9	15.1	18.6	1756
Yakima AP	3315	−11.8	31.4/17.5	17.4	18.2	1304
WEST VIRGINIA						
Beckley	3088	−11.7	27.0/20.1	9.6	21.2	1494
Charleston AP	2581	−10.9	30.1/22.2	10.6	23.4	2031

Table B.3 Outdoor Design Conditions: United States and Canada (SI units) *(Continued)*

	Winter		Summer			
State and Station[a]	HDD18.3°C	Design Dry-Bulb (°C) (99%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2%)	CDD10.0°C
Huntington CO	2592	−10.8	30.4/22.6	10.6	23.8	2008
Morgantown	2979	−11.6	29.2/21.3	11.0	22.7	1753
WISCONSIN						
Eau Claire AP	4628	−24.2	28.9/20.8	11.3	22.3	1337
Green Bay AP	4494	−21.1	27.9/21.2	11.2	22.4	1209
La Cross AP	4162	−21.8	29.8/22.0	11.1	23.5	1550
Madison AP	4263	−20.4	29.0/21.5	11.7	22.7	1327
Milwaukee AP	4069	−17.7	28.4/21.5	8.9	22.8	1327
WYOMING						
Casper AP	4268	−20.2	30.7/14.5	17.4	15.8	1157
Cheyenne AP	4070	−17.4	28.1/13.9	14.3	15.6	1048
Lander AP	4383	−21.2	29.7/14.0	15.2	15.2	1213
Laramie AP	5004	−19.3	26.2/11.9	16.2	13.4	687
Rock Springs AP	4647	−17.6	27.7/11.9	15.1	13.0	963
Sheridan AP	4336	−22.1	30.7/16.5	16.5	17.6	1124
ALBERTA						
Calgary AP	5492	−26.2	24.6/14.2	12.2	15.1	648
Edmonton AP	6124	−29.6	23.8/15.8	11.7	16.6	594
Medicine Hat AP	4993	−27.9	28.6/16.6	13.7	16.9	1101
BRITISH COLUMBIA						
Prince George AP	5275	−27.2	23.4/14.3	12.2	15.0	503
Prince Rupert CO	4250	−9.3	16.4/13.4	5.1	14.1	318
Vancouver AP	3157	−4.5	21.9/16.9	7.6	17.3	853
Victoria CO	3052	−2.9	22.5/15.9	10.0	16.3	714
MANITOBA						
The Pas	6939	−32.8	24.7/16.8	10.3	17.9	684
Winnipeg AP	6032	−30.2	27.1/18.9	11.4	20.1	991
NEW BRUNSWICK						
Fredericton AP	4814	−21.3	26.4/18.8	11.3	20.1	906
Saint John AP	4876	−19.8	22.8/16.7	9.6	17.9	655
NEWFOUNDLAND						
Gander	5197	−17.9	22.6/16.7	9.8	17.8	597
St. John's AP	4938	−14.1	21.3/17.1	8.8	18.0	471
NORTHWEST TERR.						
Fort Smith AP	7884	−37.9	24.3/15.4	11.6	16.4	518
Inuvik	10,227	−41.7	21.8/14.0	10.1	14.6	272
Yellowknife AP	8642	−39.4	21.8/14.2	7.9	15.1	473
NOVA SCOTIA						
Halifax AP	4518	−16.5	24.2/18.1	9.1	19.4	813
Sydney AP	4646	−16.0	23.7/18.2	9.5	19.2	715
Yarmouth AP	4175	−12.0	20.6/17.5	7.3	18.2	656

Table B.3 Outdoor Design Conditions: United States and Canada (SI units) *(Continued)*

		Winter			*Summer*	
State and Station[a]	**HDD18.3°C**	**Design Dry-Bulb (°C) (99%)**	**Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)**	**Mean Daily Range (°C)**	**Design Wet-Bulb (°C) (2%)**	**CDD10.0°C**
ONTARIO						
Ottawa AP	4762	–21.8	27.0/19.5	14.3	20.8	1136
Sudbury AP	5550	–25.4	25.6/17.8	10.5	19.3	865
Thunder Bay	5868	–27.3	24.9/17.9	12.1	18.9	666
Toronto AP	4059	–16.7	27.3/20.1	10.6	21.3	1317
PRINCE EDWARD ISLAND						
Charlottetown AP	4777	–18.6	23.7/18.6	8.4	19.6	778
QUEBEC						
Montréal AP	4603	–21.4	26.7/20.1	9.5	21.2	1192
Québec AP	5249	–23.9	25.6/19.0	10.2	20.3	873
Sept Iles AP	6271	–26.2	19.4/14.8	7.4	15.7	383
Trois Rivières	5069	–22.8	24.6/20.2	6.7	21.1	981
Val d'Or AP	6253	–30.3	25.0/17.4	11.2	18.7	663
SASKATCHEWAN						
Prince Albert AP	6672	–34.2	25.3/16.4	11.7	17.5	696
Regina AP	5985	–31.2	27.3/16.9	12.7	18.1	900
Saskatoon AP	6177	–32.2	26.5/16.6	12.4	17.6	854
YUKON TERRITORY						
Whitehorse AP	7109	–37.3	20.9/12.2	11.6	12.8	339

[a]U.S. solar data are available from the National Climatic Data Center, Federal Building, Asheville, NC 28801. Canadian solar data are available from The Canadian Climate Center, Atmospheric Environment Service, 4905 Dufferin St., Downsview, Ontario M3H 5T4.

Table B.4 Outdoor Design Conditions: Mexico and Puerto Rico (SI units)

		Winter			*Summer*	
State and Station	**HDD18.3°C**	**Design Dry-Bulb (°C) (99%)**	**Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2%)**	**Mean Daily Range (°C)**	**Design Wet-Bulb (°C) (2%)**	**CDD10.0°C**
MEXICO						
Guadalajara	389	3.8	31.2/15.6	10.3	19.4	—
Mérida	6	15.8	35.9/24.3	10.8	26.5	617
Mexico City	668	5.8	26.9/13.6	10.4	15.7	2646
Monterrey	469	5.2	36.9/23.6	12.1	25.4	4626
PUERTO RICO						
San Juan	0	21.4	31.8/25.4	5.8	26.5	6337

Table B.5 Legacy Outdoor Design Conditions: United States and Canada (I-P units)

	Winter			Summer		
State and Station[a]	**HDD65°F**	**Design Dry-Bulb (°F) (97.5%)**	**Design Dry-Bulb and Mean Coincident Wet Bulb (°F) (2.5%)**	**Mean Daily Range (°F)**	**Design Wet-Bulb (°F) (2.5%)**	**CDD74°F**
CALIFORNIA						
Barstow AP	2585	29	104/68	37	71	27584
Los Angeles AP	1595	43	80/68	15	69	4306
Los Angeles CO	1210	40	89/70	20	71	10575
Needles AP	1394	33	110/71	27	75	65218
Oakland AP	2880	36	80/63	19	64	435
Pomona CO	1973	30	99/69	36	72	10240
Redding AP	2548	31	102/67	32	69	27881
Sacramento AP	2775	32	98/70	36	71	10464
San Diego AP	1284	44	80/69	12	70	4643
San Luis Obispo	2503	35	88/70	26	71	1085
Santa Monica CO	1873	43	80/68	16	69	1908
COLORADO						
Denver AP	6023	1	91/59	28	63	5908
Leadville	—	–4	81/51	30	55	—
CONNECTICUT						
New Haven AP	—	7	84/73	17	75	—
GEORGIA						
Rome AP	3136	22	93/76	23	78	17745
HAWAII						
Wahiawa	—	59	85/72	14	74	—
IDAHO						
Moscow	6691	0	87/62	32	64	1986
ILLINOIS						
Carbondale	4568	7	93/77	21	79	14114
INDIANA						
Muncie	—	2	90/73	22	76	—
IOWA						
Ames	6882	–6	90/74	23	76	7453
Iowa City	6378	–6	89/76	22	78	10098
MARYLAND						
Cumberland	5108	10	89/74	22	76	7088
Hagerstown	5092	12	91/74	22	76	7346
MASSACHUSETTS						
Springfield	5955	0	87/71	19	73	5205
MISSISSIPPI						
Vicksburg CO	2200	26	95/78	21	80	24595
MISSOURI						
Springfield AP	4665	9	93/74	23	77	16262
MONTANA						
Billings AP	7220	–10	91/64	31	66	6167

Table B.5 Legacy Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

	Winter				*Summer*	
State and Station[a]	**HDD65°F**	**Design Dry-Bulb (°F) (97.5%)**	**Design Dry-Bulb and Mean Coincident Wet Bulb (°F) (2.5%)**	**Mean Daily Range (°F)**	**Design Wet-Bulb (°F) (2.5%)**	**CDD74°F**
NEBRASKA						
Omaha AP	6201	–3	91/75	22	77	13180
NEVADA						
Las Vegas AP	2535	28	106/65	30	70	43153
NEW JERSEY						
Trenton CO	4953	14	88/74	19	76	7393
NEW MEXICO						
Albuquerque AP	4415	16	94/61	27	65	11012
Las Cruces	3120	20	96/64	30	68	14507
Los Alamos	6389	9	87/60	32	61	1235
NEW YORK						
Buffalo AP	6799	6	85/70	21	73	3044
Ithaca	7182	0	85/71	24	73	1583
NORTH DAKOTA						
Williston	9252	–21	88/67	25	70	4034
OKLAHOMA						
Norman	—	13	96/74	24	76	—
Oklahoma City AP	3742	13	97/74	23	77	22978
Stillwater	3802	13	96/74	24	76	23621
OREGON						
Bend	7082	4	87/60	33	62	647
Eugene AP	4803	22	89/66	31	67	1296
Medford AP	4803	23	94/67	35	68	6151
Portland AP	4693	23	85/67	23	67	1851
Portland CO	4417	24	86/67	21	67	2105
Salem AP	4978	23	88/66	31	68	1081
PENNSYLVANIA						
Harrisburg AP	5339	11	91/74	21	76	9071
Scranton/Wilkes-Barre	6332	5	87/71	19	73	3774
State College	6252	7	87/71	23	73	3484
RHODE ISLAND						
Newport	6122	9	85/72	16	75	1682
SOUTH CAROLINA						
Spartanburg AP	3246	22	91/74	20	76	14069
TEXAS						
Bryan AP	1784	29	96/76	20	78	33178
Sherman Perrin AFB	2943	20	98/75	22	77	29686
UTAH						
Vernal AP	7671	0	89/60	32	63	2678
VERMONT						
Barre	8529	–11	81/69	23	71	1377

Table B.5 Legacy Outdoor Design Conditions: United States and Canada (I-P units) *(Continued)*

		Winter			*Summer*	
State and Station[a]	**HDD65°F**	**Design Dry-Bulb (°F) (97.5%)**	**Design Dry-Bulb and Mean Coincident Wet Bulb (°F) (2.5%)**	**Mean Daily Range (°F)**	**Design Wet-Bulb (°F) (2.5%)**	**CDD74°F**
VIRGINIA						
Charlottesville	4195	18	91/74	23	76	10287
WASHINGTON						
Seattle CO	4684	27	82/66	19	67	897
Seattle–Tacoma AP	5122	26	80/64	22	64	1050
WEST VIRGINIA						
Wheeling	5456	5	86/71	21	73	6793
WISCONSIN						
Ashland	9067	–16	82/68	23	70	1288
BRITISH COLUMBIA						
Vancouver AP	5454	19	77/66	17	67	221
MANITOBA						
Flin Flon	12551	–37	81/66	19	68	1424
NEWFOUNDLAND						
Corner Brook	8550	0	73/63	17	66	505
ONTARIO						
Kitchener	7463	–2	85/72	23	74	2447
QUEBEC						
Chicoutimi	9781	–22	83/68	20	70	1135

[a]U.S. solar data are available from the National Climatic Data Center, Federal Building, Asheville, NC 28801. Canadian solar data are available from The Canadian Climate Center, Atmospheric Environment Service, 4905 Dufferin St., Downsview, Ontario M3H 5T4.

Table B.6 Legacy Outdoor Design Conditions: United States and Canada (SI units)

	Winter					Summer
State and Station[a]	HDD18°C	Design Dry-Bulb (°C) (97.5%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2.5%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2.5%)	CDH23°C
CALIFORNIA						
Barstow AP	1436	–2	40/20	21	22	15,324
Los Angeles AP	886	6	27/20	8	21	2392
Los Angeles CO	672	4	32/21	11	22	5875
Needles AP	774	1	43/22	15	24	3623
Oakland AP	1600	2	27/17	11	18	242
Pomona CO	1096	–1	37/21	20	22	5689
Redding AP	1416	–1	39/19	18	21	15,489
Sacramento AP	1542	0	37/21	20	22	5813
San Diego AP	713	7	27/21	7	21	2579
San Luis Obispo	1391	2	31/21	14	22	603
Santa Monica CO	1041	6	27/20	9	21	1060
COLORADO						
Denver AP	3346	–17	33/15	16	17	3282
Leadville	—	–20	27/11	17	13	—
CONNECTICUT						
New Haven AP	—	–14	29/23	9	24	—
GEORGIA						
Rome AP	1742	–6	34/24	13	26	9858
HAWAII						
Wahiawa	—	15	29/22	8	24	—
IDAHO						
Moscow	3717	–18	31/17	18	18	1103
ILLINOIS						
Carbondale	2538	–14	34/25	12	26	7841
INDIANA						
Muncie	—	–17	32/23	12	24	—
IOWA						
Ames	3823	–21	32/23	13	24	4141
Iowa City	3543	–21	32/24	12	26	5610
MARYLAND						
Cumberland	2838	–12	32/23	12	24	3938
Hagerstown	2829	–11	33/23	12	24	4081
MASSACHUSETTS						
Springfield	3308	–18	31/22	11	23	2892
MISSISSIPPI						
Vicksburg CO	1222	–3	35/26	12	27	13,664
MISSOURI						
Springfield AP	2592	–13	34/23	13	25	9034
MONTANA						
Billings AP	4011	–23	33/18	17	19	3426

State and Station[a]	Winter HDD18°C	Design Dry-Bulb (°C) (97.5%)	Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2.5%)	Mean Daily Range (°C)	Design Wet-Bulb (°C) (2.5%)	Summer CDH23°C
NEBRASKA						
Omaha AP	3445	−19	33/24	12	25	7322
NEVADA						
Las Vegas AP	1408	−2	41/18	17	21	23,974
NEW JERSEY						
Trenton CO	2752	−10	31/23	11	24	4107
NEW MEXICO						
Albuquerque AP	2453	−9	34/16	15	18	6118
Las Cruces	1733	−7	36/18	17	20	8059
Los Alamos	3549	−13	31/16	18	16	686
NEW YORK						
Buffalo AP	3777	−14	29/21	12	23	1691
Ithaca	3990	−18	29/22	13	23	879
NORTH DAKOTA						
Williston	5140	−29	31/19	14	21	2241
OKLAHOMA						
Norman	—	−11	36/23	13	24	—
Oklahoma City AP	2079	−11	36/23	13	25	12,766
Stillwater	2112	−11	36/23	13	24	13,123
OREGON						
Bend	3934	−16	31/16	18	17	359
Eugene AP	2668	−6	32/19	17	19	720
Medford AP	2668	−5	35/19	19	20	3417
Portland AP	2607	−5	29/19	13	19	1028
Portland CO	2454	−4	30/19	12	19	1169
Salem AP	2766	−5	31/19	17	20	601
PENNSYLVANIA						
Harrisburg AP	2966	−12	33/23	12	24	5039
Scranton/Wilkes-Barre	3518	−15	31/22	11	23	2097
State College	3473	−14	31/22	13	23	1936
RHODE ISLAND						
Newport	3401	−13	29/22	9	24	934
SOUTH CAROLINA						
Spartanburg AP	1803	−6	33/23	11	24	7816
TEXAS						
Bryan AP	991	−2	36/24	11	26	18,432
Sherman Perrin AFB	1635	−7	37/24	12	25	16,492
UTAH						
Vernal AP	4262	−18	32/16	18	17	1488
VERMONT						
Barre	4738	−24	27/21	13	22	765

	Winter					*Summer*
State and Station[a]	**HDD18°C**	**Design Dry-Bulb (°C) (97.5%)**	**Design Dry-Bulb and Mean Coincident Wet-Bulb (°C) (2.5%)**	**Mean Daily Range (°C)**	**Design Wet-Bulb (°C) (2.5%)**	**CDH23°C**
VIRGINIA						
Charlottesville	2331	−8	33/23	13	24	5715
WASHINGTON						
Seattle CO	2602	−3	28/19	11	19	498
Seattle–Tacoma AP	2846	−3	27/18	12	18	583
WEST VIRGINIA						
Wheeling	3031	−15	30/22	12	23	3774
WISCONSIN						
Ashland	5037	−27	28/20	13	21	716
BRITISH COLUMBIA						
Vancouver AP	3030	−7	25/19	9	19	123
MANITOBA						
Flin Flon	6973	−38	27/19	11	20	791
NEWFOUNDLAND						
Corner Brook	4750	−18	23/17	9	19	281
ONTARIO						
Kitchener	4146	−19	29/22	13	23	1359
QUEBEC						
Chicoutimi	5434	−30	28/20	11	21	631

[a]U.S. solar data are available from the National Climatic Data Center, Federal Building, Asheville, NC 28801. Canadian solar data are available from The Canadian Climate Center, Atmospheric Environment Service, 4905 Dufferin St., Downsview, Ontario M3H 5T4.

APPENDIX C

Solar and Daylighting Design Data

This appendix contains the following information:

- *Solar Intensity and Solar Heat Gain Factors* (Tables C.1–C.10). These values are listed for five latitudes (16, 32, 40, 48, and 64 °N) in both I-P and SI units (the tables are so labeled). Solar heat gain factors represent the solar radiation gain through one layer of double-strength sheet (DSA) glass. The data are based on an "average cloudless" day at the respective latitudes. Tables C.1 through C.10 are copyrighted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, and are reprinted by permission from the 1997 *ASHRAE Handbook—Fundamentals*.
- *Solar Position and Clear-Day Global Irradiance (Insolation) (Tables* C.11–C.18*)*. These values are listed for four latitudes (32, 40, 48, and 64 °N). The data are presented in I-P and SI units for the following tilt angles (degrees above the horizontal): latitude −10°, latitude, latitude +10°, latitude +20°, and vertical.
- *Elevation, Latitude, Average Horizontal Insolation, Average Vertical Insolation, Average Temperature, and Heating Degree Days (Tables* C.19 *and* C.20*)*. These values are listed in I-P and SI units for January and July, along with yearly totals, for a number of locations (see Fig. C.1).
- *Daylighting Coefficient of Utilization Values for Various Window and Sky Configurations (Tables* C.21–C.26*)*.
- *Reflectances of Materials Used to Construct Daylighting Models (Table* C.27*)*.

TABLE C.1 Solar Intensity and Solar Heat Gain Factors[a] for 16° N Latitude (I-P units)[b]

Date	Solar Time A.M.	Direct Normal Btu/h ft²	*Solar Heat Gain Factors, Btu/h ft²* N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time P.M.
Jan 21	7	141	5	6	44	92	124	134	126	96	49	6	5	5	5	5	5	5	14	5
	8	262	14	15	55	147	210	240	233	189	114	25	14	14	14	14	14	14	79	4
	9	300	21	21	32	122	200	244	251	219	152	58	22	21	21	21	21	21	150	3
	10	317	26	26	27	66	150	209	233	223	178	102	31	26	26	26	26	26	203	2
	11	325	29	29	29	31	77	148	195	210	194	146	75	31	29	29	29	29	236	1
	12	327	30	30	30	30	32	73	139	184	199	184	138	72	32	30	30	30	248	12
HALF-DAY TOTALS			110	112	196	461	760	1000	1096	1020	781	426	211	127	111	110	110	110	805	
Feb 21	7	182	8	17	84	138	169	172	150	103	36	8	8	8	8	8	8	8	25	5
	8	273	17	19	96	180	231	247	224	166	77	18	17	17	17	17	17	17	101	4
	9	305	23	24	64	153	214	242	233	188	110	30	23	23	23	23	23	23	174	3
	10	319	28	29	33	92	161	202	211	188	134	61	30	28	28	28	28	28	229	2
	11	326	32	32	32	37	83	136	167	172	149	102	49	33	32	32	32	32	263	1
	12	328	33	33	33	33	34	60	107	142	154	142	106	60	34	33	33	33	275	12
HALF-DAY TOTALS			124	137	321	609	865	1023	1034	885	582	287	174	132	124	124	124	124	930	
Mar 21	7	201	11	53	124	172	192	183	145	82	15	10	10	10	10	10	10	10	40	5
	8	272	20	50	140	205	239	235	195	123	35	19	19	19	19	19	19	19	120	4
	9	299	26	35	109	179	218	225	197	138	57	27	26	26	26	26	26	26	192	3
	10	312	31	33	61	120	165	182	172	134	76	34	32	31	31	31	31	31	247	2
	11	318	34	35	36	53	87	114	125	116	89	55	36	35	34	34	34	34	280	1
	12	320	35	35	36	36	37	47	69	87	93	86	68	47	37	38	36	35	291	12
HALF-DAY TOTALS			141	226	494	755	928	975	879	643	319	187	153	142	139	139	139	139	1025	
Apr 21	6	14	2	8	12	14	14	12	8	2	1	1	1	1	1	1	1	1	1	6
	7	197	24	94	153	187	191	167	117	45	14	13	13	13	13	13	13	13	53	5
	8	256	27	99	172	216	227	204	150	69	24	22	22	22	22	22	22	22	131	4
	9	280	31	79	149	193	208	193	147	77	31	29	29	29	29	29	29	29	197	3
	10	293	35	54	102	141	158	151	120	73	37	34	33	33	33	33	33	33	249	2
	11	299	38	40	54	72	86	88	78	60	43	38	38	36	36	36	36	37	279	1
	12	301	39	39	39	40	40	41	43	45	45	45	43	41	40	39	39	39	289	12
HALF-DAY TOTALS			179	403	674	859	922	851	653	352	174	159	157	156	155	155	155	156	1057	
May 21	6	44	14	30	41	45	43	34	19	4	3	3	3	3	3	3	3	3	5	6
	7	193	50	120	168	191	185	150	92	24	16	16	16	16	16	16	16	17	62	5
	8	244	52	132	189	218	215	179	115	38	25	24	24	24	24	24	24	25	135	4
	9	268	49	116	171	198	197	167	109	45	32	30	30	30	30	30	30	32	197	3
	10	280	47	89	130	151	150	126	84	44	37	35	35	35	35	35	35	37	245	2
	11	286	47	63	79	87	83	70	52	41	40	39	38	38	38	39	39	41	273	1
	12	288	46	46	44	43	42	41	41	41	41	41	41	41	42	43	44	46	282	12
HALF-DAY TOTALS			283	575	804	916	897	748	493	217	172	167	167	167	167	168	169	176	1058	
Jun 21	6	53	20	39	52	55	51	39	20	4	4	4	4	4	4	4	4	4	7	6
	7	188	62	128	172	190	179	141	80	20	16	16	16	16	16	16	16	18	64	5
	8	238	66	142	194	217	207	167	99	31	25	25	25	25	25	25	25	27	135	4
	9	261	63	130	178	198	190	154	93	37	31	31	31	31	31	31	31	33	194	3
	10	273	59	104	140	154	145	115	70	39	37	36	36	36	36	36	36	38	241	2
	11	279	57	76	90	92	82	63	46	41	40	39	39	39	39	40	41	43	268	1
	12	281	57	55	50	45	43	42	41	41	41	41	41	42	42	45	50	55	277	12
HALF-DAY TOTALS			356	648	850	929	876	700	430	194	174	171	171	171	172	173	176	190	1049	
Jul 21	6	41	14	29	39	42	40	31	18	4	3	3	3	3	3	3	3	3	6	6
	7	184	51	118	164	185	179	145	88	23	16	16	16	16	16	16	16	17	62	5
	8	236	55	132	187	214	210	174	111	37	25	25	25	25	25	25	25	26	133	4
	9	259	52	117	170	196	193	163	106	44	32	31	31	31	31	31	31	33	194	3
	10	272	50	92	131	151	148	123	81	44	38	36	36	36	36	36	36	38	241	2
	11	278	49	66	81	88	83	69	52	42	41	40	39	39	39	40	40	42	289	1
	12	279	49	48	46	44	43	42	42	42	42	42	42	42	43	44	46	48	277	12
HALF-DAY TOTALS			296	580	799	903	878	729	478	215	176	172	171	171	171	172	173	182	1043	
Aug 21	6	11	2	7	10	12	12	10	6	2	1	1	1	1	1	1	1	1	1	6
	7	180	26	92	145	176	180	156	109	42	15	14	14	14	14	14	14	14	53	5
	8	240	30	100	168	209	219	196	143	65	25	23	23	23	23	23	23	23	128	4
	9	266	33	82	148	190	203	187	142	74	33	30	30	30	30	30	30	30	193	3
	10	279	37	58	104	140	155	147	117	71	39	36	35	35	35	35	35	35	243	2
	11	285	40	43	57	75	86	87	76	59	44	40	39	38	38	38	38	39	273	1
	12	287	41	41	41	42	42	43	44	45	46	45	44	43	42	41	41	41	282	12
HALF-DAY TOTALS			191	410	666	837	891	817	624	339	180	167	165	164	163	163	163	164	1033	
Sep 21	7	179	12	50	114	158	176	168	133	76	15	11	11	11	11	11	11	11	39	5
	8	253	21	49	134	196	227	224	186	119	36	20	20	20	20	20	20	20	116	4
	9	281	28	36	106	173	211	217	191	134	57	28	27	27	27	27	27	27	185	3
	10	295	32	34	61	118	161	178	168	132	76	35	33	32	32	32	32	32	236	2
	11	302	35	36	37	54	86	113	123	114	88	56	38	36	35	35	35	35	271	1
	12	304	36	36	37	38	39	49	69	86	93	86	69	48	39	38	37	36	282	12
HALF-DAY TOTALS			146	226	475	722	885	931	842	622	319	192	159	148	145	144	144	144	991	
Oct 21	7	166	8	18	79	128	156	159	139	95	33	9	8	8	8	8	8	8	25	5
	8	259	17	20	95	174	223	237	215	159	74	19	17	17	17	17	17	17	99	4
	9	292	24	25	65	150	209	235	225	187	106	31	24	24	24	24	24	24	170	3
	10	307	29	30	34	92	158	197	205	183	130	60	31	29	29	29	29	29	224	2
	11	314	32	32	33	39	83	133	163	167	145	100	49	34	32	32	32	32	258	1
	12	316	33	33	33	34	35	60	105	139	150	138	104	60	35	34	33	33	270	12
HALF-DAY TOTALS			127	141	318	592	836	986	996	852	563	283	175	136	128	127	127	127	911	
Nov 21	7	134	5	6	43	89	119	129	120	92	47	6	5	5	5	5	5	5	14	5
	8	255	15	15	55	145	206	235	228	185	111	25	15	15	15	15	15	15	78	4
	9	295	21	21	33	121	197	241	247	215	150	57	22	21	21	21	21	21	149	3
	10	312	26	26	28	67	147	206	230	220	176	100	31	26	26	26	26	26	201	2
	11	320	29	29	29	31	77	146	192	207	191	144	74	31	29	29	29	29	234	1
	12	322	30	30	30	30	32	72	137	181	196	181	137	72	32	30	30	30	246	12
HALF-DAY TOTALS			112	113	197	456	749	983	1077	1001	767	420	210	128	112	112	112	112	799	
Dec 21	7	118	4	5	30	72	101	112	107	85	48	7	4	4	4	4	4	4	10	5
	8	255	13	14	41	132	198	233	231	193	124	33	13	13	13	13	13	13	69	4
	9	297	20	20	25	108	191	241	254	227	165	72	21	20	20	20	20	20	138	3
	10	315	25	25	26	56	144	208	239	233	192	117	35	25	25	25	25	25	191	2
	11	323	28	28	28	29	73	150	202	221	207	161	86	30	28	28	28	28	223	1
	12	325	29	29	29	29	30	77	149	197	212	196	149	76	30	29	29	29	234	12
HALF-DAY TOTALS			104	105	159	402	710	975	1099	1050	836	484	228	125	105	104	104	104	748	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.2 Solar Intensity and Solar Heat Gain Factors[a] for 32° N Latitude (I-P units)[b]

Date	Solar Time A.M.	Direct Normal Btu/h ft²	Solar Heat Gain Factors, Btu/h ft² N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time P.M.
Jan 21	7	141	5	6	44	92	124	134	126	96	49	6	5	5	5	5	5	5	14	5
	8	203	9	9	29	105	160	189	189	159	103	28	9	9	9	9	9	9	32	4
	9	269	15	15	17	91	175	229	246	225	169	82	17	15	15	15	15	15	88	3
	10	295	20	20	20	41	135	209	249	250	212	141	46	20	20	20	20	20	136	2
	11	306	23	23	23	24	68	159	221	249	238	191	110	29	23	23	23	23	166	1
	12	310	24	24	24	24	25	88	174	228	246	228	174	88	25	24	24	24	176	12
HALF-DAY TOTALS			79	79	107	284	570	856	1015	1014	853	553	264	112	80	79	79	79	512	
Feb 21	7	112	4	7	47	82	102	106	95	67	26	4	4	4	4	4	4	4	9	5
	8	245	13	14	65	149	205	228	216	170	95	17	13	13	13	13	13	13	64	4
	9	287	19	19	32	122	199	242	248	216	149	55	20	19	19	19	19	19	127	3
	10	305	24	24	25	62	151	213	241	232	189	112	31	24	24	24	24	24	176	2
	11	314	26	26	26	28	76	156	208	227	212	165	87	28	26	26	26	26	207	1
	12	316	27	27	27	27	29	79	155	204	221	204	155	79	29	27	27	27	217	12
HALF-DAY TOTALS			100	103	201	445	735	978	1080	1010	780	452	228	122	100	100	100	100	691	
Mar 21	7	185	10	37	105	153	176	173	142	88	20	9	9	9	9	9	9	9	32	5
	8	260	17	25	107	183	227	237	209	150	62	18	17	17	17	17	17	17	100	4
	9	290	23	25	64	151	210	237	227	183	107	30	23	23	23	23	23	23	164	3
	10	304	28	28	30	87	158	202	215	195	144	70	29	28	28	28	28	28	211	2
	11	311	31	31	31	34	82	142	179	188	168	120	59	32	31	31	31	31	242	1
	12	313	32	32	32	32	33	66	122	162	176	162	122	66	33	32	32	32	252	12
HALF-DAY TOTALS			124	162	359	629	875	1033	1041	888	589	326	193	136	125	124	124	124	874	
Apr 21	6	66	9	35	54	65	66	56	38	12	4	3	3	3	3	3	3	3	7	6
	7	206	17	80	146	188	200	182	136	65	16	14	14	14	14	14	14	14	61	5
	8	255	23	61	144	200	227	219	177	107	30	22	22	22	22	22	22	22	129	4
	9	278	28	36	103	168	206	212	187	133	58	29	28	28	28	28	28	28	188	3
	10	290	32	34	52	108	155	177	172	141	87	39	33	32	32	32	32	32	233	2
	11	295	35	35	36	47	83	118	135	132	108	70	40	36	35	35	35	35	262	1
	12	297	36	36	36	37	38	53	82	106	115	106	82	53	38	37	36	36	271	12
HALF-DAY TOTALS			161	296	550	792	952	992	889	645	360	228	177	157	153	152	152	152	1015	
May 21	6	119	33	77	108	121	116	94	56	13	8	8	8	8	8	8	8	9	21	6
	7	211	36	111	170	202	204	174	118	42	19	18	18	18	18	18	18	19	81	5
	8	250	29	94	165	208	220	199	149	73	27	25	25	25	25	25	25	25	146	4
	9	269	33	61	128	177	198	190	155	93	37	32	31	31	31	31	31	31	201	3
	10	280	36	40	76	121	150	156	138	99	54	37	35	35	35	35	35	35	243	2
	11	285	38	39	42	59	83	99	102	90	68	47	40	39	37	37	37	37	269	1
	12	286	38	39	40	40	41	47	59	70	74	70	59	47	41	40	40	39	277	12
HALF-DAY TOTALS			222	438	702	900	985	933	747	447	250	199	183	177	175	174	174	175	1098	
Jun 21	6	131	44	92	123	135	127	99	55	12	10	10	10	10	10	10	10	11	28	6
	7	210	47	122	176	204	201	168	108	35	20	20	20	20	20	20	20	21	88	5
	8	245	36	106	171	208	214	189	135	60	28	27	27	27	27	27	27	27	151	4
	9	264	35	74	137	178	193	180	139	77	35	32	32	32	32	32	32	32	204	3
	10	274	38	47	86	125	146	145	123	83	45	38	36	36	36	36	36	36	244	2
	11	279	40	41	47	64	82	91	89	75	56	43	41	40	39	39	39	39	269	1
	12	280	41	41	41	42	42	46	52	58	60	58	52	46	42	42	41	41	276	12
HALF-DAY TOTALS			261	504	762	935	985	897	678	372	225	197	189	185	184	184	183	186	1122	
Jul 21	6	113	34	76	105	117	113	90	53	12	9	9	9	9	9	9	9	9	22	6
	7	203	38	111	167	198	198	169	114	41	20	19	19	19	19	19	19	19	81	5
	8	241	31	95	163	204	215	194	145	70	28	26	26	26	26	26	26	26	145	4
	9	261	34	64	129	175	195	186	150	90	37	32	32	32	32	32	32	32	198	3
	10	271	37	42	78	121	148	153	134	96	53	38	36	36	36	36	36	36	240	2
	11	277	39	40	43	60	83	98	99	88	66	47	41	40	38	38	38	38	265	1
	12	279	40	40	41	41	42	48	58	68	72	68	58	48	42	41	41	40	273	12
HALF-DAY TOTALS			231	444	701	890	967	912	726	433	248	202	187	182	180	179	179	180	1088	
Aug 21	6	59	10	33	50	60	60	51	34	11	4	4	4	4	4	4	4	4	8	6
	7	190	19	79	141	179	190	172	128	61	17	15	15	15	15	15	15	15	61	5
	8	240	25	63	141	195	219	210	170	102	31	23	23	23	23	23	23	23	128	4
	9	263	30	39	104	166	200	206	181	127	57	31	29	29	29	29	29	29	185	3
	10	276	34	36	55	109	153	173	167	136	84	40	35	34	34	34	34	34	229	2
	11	282	36	37	39	50	84	116	131	127	104	69	41	38	36	36	36	36	256	1
	12	284	37	37	37	39	40	54	81	103	111	103	81	54	40	39	37	37	265	12
HALF-DAY TOTALS			171	303	546	774	922	955	854	618	352	231	184	166	162	161	160	160	999	
Sep 21	7	163	10	35	96	139	159	156	128	80	20	10	10	10	10	10	10	10	31	5
	8	240	18	26	103	173	215	224	198	143	60	19	18	18	18	18	18	18	96	4
	9	272	24	26	64	146	202	227	218	177	105	31	24	24	24	24	24	24	158	3
	10	287	29	29	32	86	154	196	208	189	141	70	31	29	29	29	29	29	204	2
	11	294	32	32	32	36	81	139	174	182	163	118	59	34	32	32	32	32	234	1
	12	296	33	33	33	33	35	66	120	158	171	158	120	66	35	33	33	33	244	12
HALF-DAY TOTALS			130	164	345	598	831	982	993	852	574	325	197	142	130	129	129	129	845	
Oct 21	7	99	4	7	43	74	92	96	85	60	24	5	4	4	4	4	4	4	10	5
	8	229	13	15	63	143	195	217	206	162	90	17	13	13	13	13	13	13	63	4
	9	273	20	20	33	120	193	234	239	208	144	54	21	20	20	20	20	20	125	3
	10	293	24	24	26	62	147	207	234	225	183	109	32	24	24	24	24	24	173	2
	11	302	27	27	27	29	76	152	203	221	207	160	85	29	27	27	27	27	203	1
	12	304	28	28	28	28	30	78	151	199	215	199	151	78	30	28	28	28	213	12
HALF-DAY TOTALS			103	106	200	433	708	941	1038	972	753	441	226	125	104	103	103	103	679	
Nov 21	7	2	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	5
	8	196	9	9	29	103	156	184	184	155	100	27	9	9	9	9	9	9	32	4
	9	263	16	16	17	90	173	225	241	221	166	80	17	16	16	16	16	16	88	3
	10	289	20	20	21	41	134	206	245	246	209	138	45	21	20	20	20	20	136	2
	11	301	23	23	23	24	67	157	218	245	234	188	109	29	23	23	23	23	165	1
	12	304	24	24	24	24	25	87	171	224	243	224	171	87	25	24	24	24	175	12
HALF-DAY TOTALS			80	81	108	282	561	841	996	995	838	544	261	113	81	80	80	80	509	
Dec 21	8	176	7	7	19	84	135	163	166	143	97	31	7	7	7	7	7	7	22	4
	9	257	14	14	15	77	162	218	238	222	171	89	15	14	14	14	14	14	72	3
	10	288	18	18	18	34	127	204	246	251	216	148	52	19	18	18	18	18	119	2
	11	301	21	21	21	22	63	157	222	252	243	197	116	29	21	21	21	21	148	1
	12	304	22	22	22	22	23	89	177	232	252	232	177	89	23	22	22	22	158	12
HALF-DAY TOTALS			71	71	84	227	500	792	965	986	852	578	275	107	71	71	71	71	440	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.3 Solar Intensity and Solar Heat Gain Factors[a] for 40° N Latitude (I-P units)[b]

Date	Solar Time A.M.	Direct Normal Btu/h ft²	Solar Heat Gain Factors, Btu/h ft²																	Solar Time P.M.
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	
Jan 21	7	141	5	6	44	92	124	134	126	96	49	6	5	5	5	5	5	5	14	5
	9	239	12	12	13	74	154	205	224	209	160	82	13	12	12	12	12	12	55	3
	10	274	16	16	16	31	124	199	241	246	213	146	51	17	16	16	16	16	96	2
	11	289	19	19	19	20	61	156	222	252	244	198	118	28	19	19	19	19	124	1
	12	294	20	20	20	20	21	90	179	234	254	234	179	90	21	20	20	20	133	12
HALF-DAY TOTALS			61	61	73	199	452	734	904	932	813	561	273	101	62	61	61	61	354	
Feb 21	7	55	2	3	23	40	51	53	47	34	14	2	2	2	2	2	2	2	4	5
	8	219	10	11	50	129	183	206	199	160	94	18	10	10	10	10	10	10	43	4
	9	271	16	16	22	107	186	234	245	218	157	66	17	16	16	16	16	16	98	3
	10	294	21	21	21	49	143	211	246	243	203	129	38	21	21	21	21	21	143	2
	11	304	23	23	23	24	71	160	219	244	231	184	103	27	23	23	23	23	171	1
	12	307	24	24	24	24	25	86	170	222	241	222	170	86	25	24	24	24	180	12
HALF-DAY TOTALS			84	86	152	361	648	916	1049	1015	821	508	250	114	85	84	84	84	548	
Mar 21	7	171	9	29	93	140	163	161	135	86	22	8	8	8	8	8	8	8	26	5
	8	250	16	18	91	169	218	232	211	157	74	17	16	16	16	16	16	16	85	4
	9	282	21	22	47	136	203	238	236	198	128	40	22	21	21	21	21	21	143	3
	10	297	25	25	27	72	153	207	229	216	171	95	29	25	25	25	25	25	186	2
	11	305	28	28	28	30	78	151	198	213	197	150	77	30	28	28	28	28	213	1
	12	307	29	29	29	29	31	75	145	191	206	191	145	75	31	29	29	29	223	12
HALF-DAY TOTALS			114	139	302	563	832	1035	1087	968	694	403	220	132	114	113	113	113	764	
Apr 21	6	89	11	46	72	87	88	76	52	18	5	5	5	5	5	5	5	5	11	6
	7	206	16	71	140	185	201	186	143	75	16	14	14	14	14	14	14	14	61	5
	8	252	22	44	128	190	224	223	188	124	41	22	21	21	21	21	21	21	123	4
	9	274	27	29	80	155	202	219	203	156	83	29	27	27	27	27	27	27	177	3
	10	286	31	31	37	92	152	187	193	170	121	56	32	31	31	31	31	41	217	2
	11	292	33	33	34	39	81	130	160	166	146	102	52	35	33	33	33	33	243	1
	12	293	34	34	34	34	36	62	108	142	154	142	108	62	36	34	34	34	252	12
HALF-DAY TOTALS			154	265	501	758	957	1051	994	782	488	296	199	157	148	147	147	147	957	
May 21	5	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	7
	6	144	36	90	128	145	141	115	71	18	10	10	10	10	10	10	10	11	31	6
	7	216	28	102	165	202	209	184	131	54	20	19	19	19	19	19	19	19	87	5
	8	250	27	73	149	199	220	208	164	93	29	25	25	25	25	25	25	25	146	4
	9	267	31	42	105	164	197	200	175	121	53	32	30	30	30	30	30	30	195	3
	10	277	34	36	54	105	148	168	163	133	83	40	35	34	34	34	34	34	234	2
	11	283	36	36	38	48	81	113	130	127	105	70	42	38	36	36	36	36	257	1
	12	284	37	37	37	38	40	54	82	114	113	104	82	54	40	38	37	37	265	12
HALF-DAY TOTALS			215	404	666	893	1024	1025	881	601	358	247	200	180	176	175	174	175	1083	
Jun 21	5	22	10	17	21	22	20	14	6	2	1	1	1	1	1	1	1	2	3	7
	6	155	48	104	143	159	151	121	70	17	13	13	13	13	13	13	13	14	40	6
	7	216	37	113	172	205	207	178	122	46	22	21	21	21	21	21	21	21	97	5
	8	246	30	85	156	201	216	199	152	80	29	27	27	27	27	27	27	27	153	4
	9	263	33	51	114	166	192	190	161	105	45	33	32	32	32	32	32	32	201	3
	10	272	35	38	63	109	145	158	148	116	69	39	36	35	35	35	35	35	238	2
	11	277	38	39	40	52	81	105	116	110	88	60	41	39	38	38	38	38	260	1
	12	279	38	38	38	40	41	52	72	89	95	89	72	52	41	40	38	38	267	12
HALF-DAY TOTALS			253	470	734	941	1038	999	818	523	315	236	204	191	188	187	186	188	1126	
Jul 21	5	2	1	2	2	2	2	1	1	0	0	0	0	0	0	0	0	0	0	7
	6	138	37	89	125	142	137	112	68	18	11	11	11	11	11	11	11	12	32	6
	7	208	30	102	163	198	204	179	127	53	21	20	20	20	20	20	20	20	88	5
	8	241	28	75	148	196	216	203	160	90	30	26	26	26	26	26	26	26	145	4
	9	259	32	44	106	163	193	196	170	118	52	33	31	31	31	31	31	31	194	3
	10	269	35	37	56	106	146	165	159	129	81	41	36	35	35	35	35	35	231	2
	11	275	37	38	40	50	81	111	127	123	102	69	43	39	37	37	37	37	254	1
	12	276	38	38	38	40	41	55	80	101	109	101	80	55	41	40	38	38	262	12
HALF-DAY TOTALS			223	411	666	885	1008	1003	858	584	352	248	204	186	181	180	180	181	1076	
Aug 21	6	81	12	44	68	81	82	71	48	17	6	5	5	5	5	5	5	5	12	6
	7	191	17	71	135	177	191	177	135	70	17	16	16	16	16	16	16	16	62	5
	8	237	24	47	126	185	216	214	180	118	41	23	23	23	23	23	23	23	122	4
	9	260	28	31	82	153	197	212	196	151	80	31	28	28	28	28	28	28	174	3
	10	272	32	33	40	93	150	182	187	165	116	56	34	32	32	32	32	32	214	2
	11	278	35	35	36	41	81	128	156	160	141	99	52	37	35	35	35	35	239	1
	12	280	35	35	35	36	38	63	106	138	149	138	106	63	38	36	35	35	247	12
HALF-DAY TOTALS			164	273	498	741	928	1013	956	751	474	296	205	166	157	156	156	156	946	
Sep 21	7	149	9	27	84	125	146	144	121	77	21	9	9	9	9	9	9	9	25	5
	8	230	17	19	87	160	205	218	199	148	71	18	17	17	17	17	17	17	82	4
	9	263	22	23	47	131	194	227	226	190	124	41	23	22	22	22	22	22	138	3
	10	280	27	27	28	71	148	200	221	209	165	93	30	27	27	27	27	27	180	2
	11	287	29	29	29	31	78	147	192	207	191	146	77	31	29	29	29	29	206	1
	12	290	30	30	30	30	32	75	142	185	200	185	142	75	32	30	30	30	215	12
HALF-DAY TOTALS			119	142	291	534	787	980	1033	925	672	396	222	137	119	118	118	118	738	
Oct 21	7	48	2	3	20	36	45	47	42	30	12	2	2	2	2	2	2	2	4	5
	8	204	11	12	49	123	173	195	188	151	89	18	11	11	11	11	11	11	43	4
	9	257	17	17	23	104	180	225	235	209	151	64	18	17	17	17	17	17	97	3
	10	280	21	21	22	50	139	205	238	235	196	125	38	22	21	21	21	21	140	2
	11	291	24	24	24	25	71	156	212	236	224	178	101	28	24	24	24	24	168	1
	12	294	25	25	25	25	27	85	165	216	234	216	165	85	27	25	25	25	177	12
HALF-DAY TOTALS			88	89	152	351	623	878	1006	974	791	493	247	117	89	88	88	88	540	
Nov 21	8	136	5	5	18	69	108	128	129	110	72	21	6	5	5	5	5	5	14	4
	9	232	12	12	13	73	151	201	219	204	156	80	13	12	12	12	12	12	55	3
	10	268	16	16	16	31	122	196	237	242	209	143	50	17	16	16	16	18	96	2
	11	283	19	19	19	20	61	154	218	248	240	194	116	28	19	19	19	19	123	1
	12	288	20	20	20	20	21	89	176	231	250	231	176	89	21	20	20	20	132	12
HALF-DAY TOTALS			63	63	75	198	445	721	887	914	798	551	269	101	63	63	63	63	354	
Dec 21	8	89	3	3	8	41	67	82	84	73	50	17	3	3	3	3	3	3	6	4
	9	217	10	10	11	60	135	185	205	194	151	83	13	10	10	10	10	10	39	3
	10	261	14	14	14	25	113	188	232	239	210	146	55	15	14	14	14	14	77	2
	11	280	17	17	17	17	56	151	217	249	242	198	120	28	17	17	17	17	104	1
	12	285	18	18	18	18	19	89	178	233	253	233	178	89	19	18	18	18	113	12
HALF-DAY TOTALS			52	52	56	146	374	649	822	867	775	557	276	94	53	52	52	52	282	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.4 Solar Intensity and Solar Heat Gain Factors[a] for 48° N Latitude (I-P units)[b]

Date	Solar Time A.M.	Direct Normal Btu/h ft²	Solar Heat Gain Factors, Btu/h ft²																	Solar Time P.M.
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	
Jan 21	7	141	5	6	44	92	124	134	126	96	49	6	5	5	5	5	5	5	14	5
	9	185	8	8	8	53	118	160	176	166	129	69	10	8	8	8	8	8	25	3
	10	239	12	12	12	22	106	175	216	223	195	136	50	12	12	12	12	12	55	2
	11	261	14	14	14	15	53	144	208	239	233	190	116	26	14	14	14	14	77	1
	12	267	15	15	15	15	16	86	171	226	245	226	171	86	16	15	15	15	85	12
HALF-DAY TOTALS			43	43	46	117	316	567	729	776	701	512	259	85	43	43	43	43	203	
Feb 21	7	4	0	0	1	3	3	3	3	2	1	0	0	0	0	0	0	0	0	5
	8	180	8	8	36	103	149	170	166	136	82	17	8	8	8	8	8	8	25	4
	9	247	13	13	16	90	168	216	230	209	155	71	14	13	13	13	13	13	66	3
	10	275	17	17	17	38	131	203	242	244	207	138	44	18	17	17	17	17	105	2
	11	288	19	19	19	20	65	158	221	249	239	192	113	27	19	19	19	19	130	1
	12	292	20	20	20	20	22	89	176	231	250	231	176	89	22	20	20	20	138	12
HALF-DAY TOTALS			68	68	107	274	541	816	968	967	813	531	261	104	68	68	68	68	395	
Mar 21	7	153	7	22	80	123	145	145	123	80	23	7	7	7	7	7	7	7	20	5
	8	236	14	15	76	154	204	222	206	158	82	15	14	14	14	14	14	14	68	4
	9	270	19	19	3	121	193	234	239	207	142	52	20	19	19	19	19	19	118	3
	10	287	23	23	24	58	146	208	237	231	189	115	33	23	23	23	23	23	156	2
	11	295	25	25	25	26	74	156	210	232	218	172	94	28	25	25	25	25	180	1
	12	298	26	26	26	26	27	83	161	211	228	211	161	83	27	26	26	26	188	12
HALF-DAY TOTALS			100	118	250	494	775	1012	1100	1014	767	465	244	126	101	100	100	100	636	
Apr 21	6	108	12	53	86	105	107	93	64	23	6	6	6	6	6	6	6	6	15	6
	7	205	15	61	132	180	199	189	148	84	18	14	14	14	14	14	14	14	60	5
	8	247	20	32	111	179	219	225	196	138	55	21	20	20	20	20	20	20	114	4
	9	268	25	26	60	141	197	223	215	176	106	33	25	25	25	25	25	25	161	3
	10	280	28	28	31	77	148	193	209	194	150	80	31	28	28	28	28	28	196	2
	11	286	31	31	31	33	78	140	181	193	177	133	69	33	31	31	31	31	218	1
	12	288	31	31	31	31	34	71	131	172	186	172	131	71	34	31	31	31	226	12
HALF-DAY TOTALS			147	242	461	724	957	1098	1081	895	605	370	226	156	141	140	140	140	875	
May 21	5	41	17	31	40	42	39	29	14	3	3	3	3	3	3	3	3	3	5	7
	6	162	35	97	141	162	160	133	85	24	12	12	12	12	12	12	12	13	40	6
	7	219	23	90	158	200	212	191	142	68	21	19	19	19	19	19	19	19	91	5
	8	248	26	54	132	190	218	214	178	113	38	25	25	25	25	25	25	25	142	4
	9	264	29	32	82	151	194	208	192	147	77	32	29	29	29	29	29	29	185	3
	10	274	33	34	39	90	145	178	184	163	116	57	35	33	33	33	33	33	219	2
	11	279	35	35	36	40	79	126	155	160	142	101	54	37	35	35	35	35	240	1
	12	280	35	35	35	36	38	63	107	139	150	139	107	63	38	36	35	35	247	12
HALF-DAY TOTALS			215	388	645	893	1065	1114	1007	749	483	316	225	184	174	173	173	174	1045	
Jun 21	5	77	35	61	76	80	72	53	24	6	5	5	5	5	5	5	5	8	12	7
	6	172	46	110	155	175	169	138	84	22	14	14	14	14	14	14	14	16	51	6
	7	220	29	101	165	204	211	187	135	60	23	21	21	21	21	21	21	21	103	5
	8	246	29	64	139	191	215	206	168	101	34	27	27	27	27	27	27	27	152	4
	9	261	31	36	91	153	190	199	180	133	66	33	31	31	31	31	31	31	193	3
	10	269	34	36	45	94	143	169	171	148	101	50	36	34	34	34	34	34	225	2
	11	274	36	36	38	44	79	118	142	145	126	88	49	38	36	36	36	36	246	1
	12	275	37	37	37	38	40	60	96	124	134	124	96	60	40	38	37	37	252	12
HALF-DAY TOTALS			257	459	722	955	1095	1102	955	678	436	299	228	197	189	188	188	191	1108	
Jul 21	5	43	18	33	42	45	41	30	15	3	3	3	3	3	3	3	3	4	6	7
	6	156	37	96	138	159	156	129	82	24	13	13	13	13	13	13	13	14	41	6
	7	211	25	90	156	196	207	186	138	66	22	20	20	20	20	20	20	20	92	5
	8	240	27	56	132	187	214	209	174	110	38	26	26	26	26	26	26	26	142	4
	9	256	30	34	83	149	191	204	187	143	75	33	30	30	30	30	30	30	184	3
	10	266	34	35	41	90	143	174	180	158	113	56	36	34	34	34	34	34	217	2
	11	271	36	36	37	42	79	124	151	156	138	99	54	38	36	36	36	36	237	1
	12	272	36	36	36	37	39	63	104	136	146	136	104	63	39	37	36	36	244	12
HALF-DAY TOTALS			223	395	646	886	1050	1092	983	730	474	315	229	190	181	179	179	180	1042	
Aug 21	6	99	13	51	81	98	100	87	60	22	7	7	7	7	7	7	7	7	16	6
	7	190	17	61	128	172	190	179	141	79	19	15	15	15	15	15	15	15	61	5
	8	232	22	34	110	174	211	216	188	132	53	23	22	22	22	22	22	22	114	4
	9	154	27	28	63	139	192	216	108	169	102	34	27	27	27	27	27	27	159	3
	10	266	30	30	33	78	145	188	203	188	144	78	33	30	30	30	30	30	193	2
	11	272	32	32	32	36	78	137	175	187	171	129	68	35	32	32	32	32	215	1
	12	274	33	33	33	33	36	71	128	167	189	167	128	71	36	33	33	33	223	12
HALF-DAY TOTALS			157	251	459	709	929	1060	1040	862	587	366	231	165	151	149	149	149	869	
Sep 21	7	131	8	21	71	108	128	128	108	71	21	8	7	7	7	7	7	7	20	5
	8	215	15	16	72	144	191	207	193	148	77	16	15	15	15	15	15	15	65	4
	9	251	20	20	34	116	184	223	227	197	136	52	21	20	20	20	20	20	114	3
	10	269	24	24	25	58	141	200	228	221	182	112	34	24	24	24	24	24	151	2
	11	278	26	26	26	28	73	151	203	223	210	166	92	29	26	26	26	26	174	1
	12	280	27	27	27	27	29	82	156	204	220	204	156	82	29	27	27	27	182	12
HALF-DAY TOTALS			105	121	240	465	729	953	1040	963	737	453	243	131	106	105	105	105	614	
Oct 21	7	4	0	0	2	3	4	4	3	2	1	0	0	0	0	0	0	0	0	5
	8	165	8	9	35	96	139	159	155	126	77	16	8	8	8	8	8	8	25	4
	9	233	14	14	16	88	161	207	220	199	148	68	15	14	14	14	14	14	66	3
	10	262	18	18	18	39	128	196	233	234	199	133	43	18	18	18	18	18	104	2
	11	274	20	20	20	21	64	153	213	241	231	186	109	27	20	20	20	20	128	1
	12	278	21	21	21	21	23	87	171	223	242	223	171	87	23	21	21	21	136	12
HALF-DAY TOTALS			71	71	108	266	519	780	925	925	779	513	256	106	72	71	71	71	391	
Nov 21	8	36	1	1	4	18	29	34	35	30	20	6	1	1	1	1	1	1	2	4
	9	179	8	8	9	52	115	156	171	161	125	67	10	8	8	8	8	8	26	3
	10	233	12	12	12	22	104	172	212	218	191	133	49	13	12	12	12	12	55	2
	11	255	15	15	15	15	52	142	204	234	228	186	114	26	15	15	15	15	77	1
	12	261	15	15	15	15	17	85	168	222	240	222	168	85	17	15	15	15	85	12
HALF-DAY TOTALS			44	44	47	117	310	555	713	760	686	502	255	85	44	44	44	44	204	
Dec 21	9	140	5	5	6	36	86	120	133	127	100	56	8	5	5	5	5	5	13	3
	10	214	10	10	10	16	91	156	194	201	179	126	49	10	10	10	10	10	38	2
	11	242	12	12	12	13	46	134	195	225	220	180	111	25	12	12	12	12	57	1
	12	250	13	13	13	13	14	81	163	215	233	215	168	81	14	13	13	13	65	12
HALF-DAY TOTALS			33	33	34	73	233	458	610	665	616	468	247	76	34	33	33	33	141	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.5 Solar Intensity and Solar Heat Gain Factors[a] for 64° N Latitude (I-P units)[b]

Date	Solar Time A.M.	Direct Normal Btu/h ft²	Solar Heat Gain Factors, Btu/h ft²																	Solar Time P.M.
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	
Jan 21	7	141	5	6	44	92	124	134	126	96	49	6	5	5	5	5	5	5	14	5
	11	81	3	3	3	3	15	45	67	77	75	62	38	8	3	3	3	3	6	1
	12	100	3	3	3	3	4	33	67	89	96	89	67	33	4	3	3	3	8	12
HALF-DAY TOTALS			5	5	5	6	25	79	121	142	141	119	75	23	5	5	5	5	11	
Feb 21	8	18	1	1	3	10	15	17	17	14	9	2	1	1	1	1	1	1	1	4
	9	134	5	5	6	43	89	118	128	119	90	45	6	5	5	5	5	5	13	3
	10	190	8	8	8	18	87	144	176	180	157	108	38	9	8	8	8	8	28	2
	11	215	10	10	10	11	44	122	177	202	197	160	97	20	10	10	10	10	41	1
	12	222	11	11	11	11	12	73	147	194	210	194	147	73	12	11	11	11	45	12
HALF-DAY TOTALS			29	30	33	89	244	446	578	617	560	411	212	66	30	29	29	29	106	
Mar 21	7	95	4	11	47	74	90	91	79	53	17	4	4	4	4	4	4	4	9	5
	8	185	9	10	46	113	158	177	170	135	78	14	9	9	9	9	9	9	32	4
	9	227	13	13	16	88	159	203	215	194	143	64	14	13	13	13	13	13	59	3
	10	249	16	16	16	35	122	190	226	228	194	130	42	16	16	16	16	16	84	2
	11	260	17	17	17	18	60	148	209	236	228	184	109	25	17	17	17	17	99	1
	12	263	18	18	18	18	19	85	168	221	239	221	168	85	19	18	18	18	105	12
HALF-DAY TOTALS			68	74	150	334	596	854	984	958	779	504	257	104	68	68	68	68	335	
Apr 21	5	27	8	18	24	27	26	20	12	2	1	1	1	1	1	1	1	1	2	7
	6	133	12	59	102	127	132	118	84	35	8	8	8	8	8	8	8	8	21	6
	7	194	14	41	113	163	189	185	153	96	25	13	13	13	13	13	13	13	51	5
	8	228	17	19	79	153	201	217	201	153	79	19	17	17	17	17	17	17	85	4
	9	248	21	21	32	111	180	219	225	197	138	55	22	21	21	21	21	21	116	3
	10	260	23	23	24	51	134	194	225	221	185	118	38	24	23	23	23	23	140	2
	11	266	24	24	24	26	68	148	202	225	214	171	99	29	24	24	24	24	155	1
	12	268	25	25	25	25	27	83	159	208	224	208	159	83	27	25	25	25	160	12
HALF-DAY TOTALS			131	218	410	671	943	1150	1186	1036	763	487	273	149	121	120	120	120	651	
May 21	4	51	30	44	51	51	43	28	8	3	3	3	3	3	3	3	3	10	6	8
	5	132	48	95	125	135	125	96	50	11	9	9	9	9	9	9	9	11	26	7
	6	185	28	97	150	181	183	158	109	40	15	15	15	15	15	15	15	15	55	6
	7	218	21	63	138	189	211	201	161	94	24	19	19	19	19	19	19	19	90	5
	8	239	23	28	97	167	209	220	198	146	68	25	23	23	23	23	23	23	124	4
	9	252	26	27	45	122	183	215	215	184	123	46	27	26	26	26	26	26	152	3
	10	261	28	28	30	61	135	188	212	205	167	102	36	28	28	28	28	28	174	2
	11	265	30	30	30	32	72	141	188	207	195	154	87	33	30	30	30	30	188	1
	12	267	30	30	30	30	33	78	146	189	204	189	146	78	33	30	30	30	192	12
HALF-DAY TOTALS			247	425	680	950	1177	1291	1218	985	708	465	288	191	169	168	168	176	911	
Jun 21	4	93	53	83	96	94	78	50	14	7	7	7	7	7	7	7	7	21	16	8
	5	154	62	114	148	158	145	110	55	14	12	12	12	12	12	12	12	14	39	7
	6	194	36	107	162	191	192	163	110	39	18	17	17	17	17	17	17	18	71	6
	7	221	24	71	145	193	213	200	158	89	25	22	22	22	22	22	22	22	105	5
	8	239	25	33	104	170	208	216	192	139	62	27	25	25	25	25	25	25	137	4
	9	251	28	29	51	124	181	210	208	175	115	43	29	28	28	28	28	28	165	3
	10	258	30	30	32	65	134	183	204	195	157	94	36	30	30	30	30	30	186	2
	11	262	32	32	32	34	72	137	180	196	184	144	82	35	32	32	32	32	199	1
	12	263	32	32	32	32	35	76	138	179	193	179	138	76	35	32	32	32	203	12
HALF-DAY TOTALS			322	533	801	1061	1253	1317	1195	946	679	455	296	211	192	190	191	213	1021	
Jul 21	4	53	32	47	55	54	46	29	9	4	4	4	4	4	4	4	4	11	8	8
	5	128	49	94	123	133	124	95	50	11	10	10	10	10	10	10	10	11	28	7
	6	179	30	96	148	177	180	155	106	39	16	15	15	15	15	15	15	15	57	6
	7	211	22	64	137	186	207	197	157	92	25	20	20	20	20	20	20	20	92	5
	8	231	24	30	97	165	205	215	193	142	67	26	24	24	24	24	24	24	124	4
	9	245	27	28	47	121	180	211	211	179	120	46	28	27	27	27	27	27	152	3
	10	253	29	29	31	62	134	185	208	200	164	100	37	29	29	29	29	29	174	2
	11	257	31	31	31	33	72	139	185	202	191	151	86	34	31	31	31	31	187	1
	12	259	31	31	31	31	34	78	143	185	200	185	143	78	34	31	31	31	192	12
HALF-DAY TOTALS			258	434	684	946	1163	1269	1193	965	697	462	292	198	177	175	175	185	918	
Aug 21	5	29	9	20	27	30	28	22	13	2	2	2	2	2	2	2	2	2	3	7
	6	123	13	58	97	121	125	111	80	34	9	9	9	9	9	9	9	9	23	6
	7	181	15	42	109	157	180	176	145	92	26	14	14	14	14	14	14	14	53	5
	8	214	19	21	78	148	193	208	192	147	76	21	19	19	19	19	19	19	87	4
	9	234	22	22	34	109	174	211	217	189	133	55	23	22	22	22	22	22	117	3
	10	246	25	25	26	52	131	188	217	214	178	114	39	25	25	25	25	25	140	2
	11	252	26	26	26	28	69	144	196	217	207	166	97	31	26	26	26	26	154	1
	12	254	27	27	27	27	29	82	155	201	217	201	155	82	29	27	27	27	159	12
HALF-DAY TOTALS			142	226	410	657	914	1109	1141	997	740	478	275	158	131	130	130	130	656	
Sep 21	7	77	4	10	39	62	74	75	65	44	15	4	4	4	4	4	4	4	8	5
	8	163	10	10	43	103	143	160	154	123	71	14	10	10	10	10	10	10	31	4
	9	206	14	14	17	83	148	189	200	181	133	61	15	14	14	14	14	14	57	3
	10	229	16	16	17	35	116	179	213	214	183	123	41	17	16	16	16	16	81	2
	11	240	18	18	18	19	59	141	198	224	216	174	104	26	18	18	18	18	96	1
	12	244	19	19	19	19	21	82	160	209	227	209	160	82	21	19	19	19	101	12
HALF-DAY TOTALS			71	77	142	307	547	787	910	891	731	480	249	106	72	71	71	71	324	
Oct 21	8	17	1	1	3	10	14	16	16	13	8	2	1	1	1	1	1	1	1	4
	9	122	5	5	6	40	82	109	118	110	83	42	6	5	5	5	5	5	13	3
	10	176	9	9	9	18	83	135	165	169	147	102	36	9	9	9	9	9	29	2
	11	201	11	11	11	11	43	116	167	191	186	152	92	20	11	11	11	11	41	1
	12	208	11	11	11	11	13	70	140	184	199	184	140	70	13	11	11	11	46	12
HALF-DAY TOTALS			31	31	34	86	231	420	542	580	527	388	202	66	32	31	31	31	108	
Nov 21	10	23	1	1	1	1	10	17	21	22	20	14	5	1	1	1	1	1	1	2
	11	79	3	3	3	3	15	44	65	75	74	61	37	8	3	3	3	3	6	1
	12	97	4	4	4	4	4	32	66	87	93	87	66	32	4	4	4	4	8	12
HALF-DAY TOTALS			5	5	5	6	26	79	120	141	140	117	74	23	6	5	5	5	11	
Dec 21	11	4	0	0	0	0	1	2	3	4	4	3	2	0	0	0	0	0	0	1
	12	16	0	0	0	0	1	5	11	14	15	14	11	5	1	0	0	0	1	12
HALF-DAY TOTALS			0	0	0	0	1	5	9	11	11	10	7	3	0	0	0	0	1	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.6 Solar Intensity and Solar Heat Gain Factors[a] for 16° N Latitude (SI units)[b]

Date	Solar Time A.M.	Direct Normal W/m²	Solar Heat Gain Factors, W/m² N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time P.M.
Jan 21	7	445	17	19	138	291	390	424	397	303	155	19	17	17	17	17	17	17	43	5
	8	827	45	48	174	463	662	757	734	596	359	79	45	45	45	45	45	45	249	4
	9	948	67	67	102	384	630	770	791	690	481	183	69	67	67	67	67	67	472	3
	10	1001	82	82	86	209	474	658	737	704	563	321	97	82	82	82	82	82	640	2
	11	1025	92	92	92	96	242	467	614	663	612	462	236	96	92	92	92	92	745	1
	12	1032	95	95	95	95	100	228	438	580	628	580	438	228	100	95	95	95	782	12
HALF-DAY TOTALS			348	352	618	1453	2398	3153	3458	3217	2465	1344	666	401	350	348	348	348	2539	
Feb 21	7	575	24	55	265	435	532	544	474	326	113	26	24	24	24	24	24	24	80	5
	8	862	53	60	304	567	729	778	706	525	244	56	53	53	53	53	53	53	319	4
	9	961	74	77	202	482	676	763	733	592	347	96	74	74	74	74	74	74	549	3
	10	1006	90	91	104	292	508	636	665	593	423	193	94	90	90	90	90	90	722	2
	11	1027	99	99	102	118	262	428	527	542	471	323	154	103	99	99	99	99	831	1
	12	1034	103	103	103	105	108	189	336	448	487	448	336	189	108	105	103	103	868	12
HALF-DAY TOTALS			390	431	1013	1922	2730	3228	3263	2792	1836	906	547	417	393	390	390	390	2933	
Mar 21	7	634	36	167	393	544	606	578	458	260	47	33	33	33	33	33	33	33	126	5
	8	857	63	157	442	648	752	741	615	390	111	61	61	61	61	61	61	61	380	4
	9	943	84	110	343	565	689	709	622	435	180	86	82	82	82	82	82	82	606	3
	10	983	98	103	191	379	519	575	543	424	240	107	100	98	98	98	98	98	778	2
	11	1003	108	110	113	166	273	361	395	366	281	173	114	110	108	108	108	108	885	1
	12	1008	111	111	112	114	117	149	216	273	295	273	216	149	117	114	112	111	919	12
HALF-DAY TOTALS			443	712	1558	2383	2926	3076	2773	2028	1006	588	483	448	440	483	437	437	3233	
Apr 21	6	44	7	24	37	43	43	37	24	7	2	2	2	2	2	2	12	2	4	6
	7	622	75	298	482	589	604	528	369	141	45	42	42	42	42	42	42	42	169	5
	8	807	85	312	543	682	718	644	473	217	74	70	70	70	70	70	70	70	413	4
	9	885	97	248	469	610	657	608	465	244	97	90	90	90	90	90	90	90	623	3
	10	924	112	171	321	444	499	476	380	231	118	109	166	106	106	106	106	106	784	2
	11	942	120	127	169	228	270	276	245	189	136	121	118	115	115	115	115	118	882	1
	12	948	123	123	124	125	126	129	135	141	143	141	135	129	126	125	124	123	911	12
HALF-DAY TOTALS			565	1272	2127	2711	2909	2684	2059	1111	547	503	494	491	490	489	490	492	3333	
May 21	6	138	43	94	128	141	134	106	59	11	9	9	9	9	9	9	9	10	195	6
	7	608	157	378	531	603	583	474	290	76	49	49	49	49	49	49	49	55	17	5
	8	771	165	415	598	689	677	564	362	121	78	76	76	76	76	76	76	80	425	4
	9	845	156	366	539	626	622	526	344	141	100	96	96	96	96	96	96	100	621	3
	10	883	149	281	410	478	474	398	264	139	116	111	111	111	111	111	111	116	772	2
	11	902	147	198	248	273	262	220	166	130	126	123	120	120	120	122	124	128	862	1
	12	907	146	144	140	134	132	131	130	129	129	129	130	131	132	134	140	144	890	12
HALF-DAY TOTALS			893	1813	2537	2891	2829	2360	1555	685	541	528	527	526	527	529	533	557	3338	
Jun 21	6	168	64	124	163	175	162	123	64	13	12	12	12	12	12	12	12	13	24	6
	7	593	195	404	543	598	565	445	252	63	52	52	52	52	52	52	52	57	203	5
	8	750	209	449	612	684	653	526	313	98	79	79	79	79	79	79	79	84	425	4
	9	823	199	409	560	626	601	487	294	118	98	98	98	98	98	98	98	105	613	3
	10	861	187	329	441	486	459	363	222	125	116	113	113	113	113	113	113	121	759	2
	11	879	181	241	283	290	258	200	146	130	126	122	122	122	122	125	128	136	847	1
	12	885	179	173	158	142	134	132	130	129	129	129	130	132	134	142	158	173	873	12
HALF-DAY TOTALS			1122	2043	2683	2930	2763	2207	1357	612	548	540	540	540	542	545	555	599	3308	
Jul 21	6	128	43	90	122	134	127	99	55	11	9	9	9	9	9	9	9	10	17	6
	7	579	161	373	518	585	564	456	277	74	51	51	51	51	51	51	51	55	194	5
	8	743	173	415	590	676	661	549	349	110	78	78	78	78	78	78	78	83	419	4
	9	818	165	371	537	618	610	513	334	138	102	99	99	99	99	99	99	104	611	3
	10	857	157	289	413	475	467	389	257	138	118	113	113	113	113	113	113	120	759	2
	11	876	154	207	255	277	262	218	164	133	128	125	122	122	122	125	128	131	848	1
	12	882	154	151	145	138	135	134	133	132	132	132	133	134	135	138	145	151	875	12
HALF-DAY TOTALS			933	1829	2521	2848	2770	2298	1507	680	554	541	539	539	540	542	547	575	3289	
Aug 21	6	136	7	21	31	37	36	31	20	6	2	2	2	2	2	2	2	2	4	6
	7	569	81	289	458	555	567	493	343	131	48	45	45	45	45	45	45	45	167	5
	8	757	94	315	531	660	691	617	451	206	79	74	74	74	74	74	74	74	404	4
	9	838	104	258	467	598	640	589	448	235	103	95	95	95	95	95	95	95	608	3
	10	879	118	183	328	443	490	464	368	224	122	114	110	110	110	110	110	110	766	2
	11	899	127	136	180	235	271	273	240	185	138	127	124	120	120	120	120	124	860	1
	12	905	129	130	130	131	132	134	139	143	145	143	139	134	132	131	130	130	889	12
HALF-DAY TOTALS			603	1294	2099	2640	2810	2578	1969	1069	568	528	519	516	515	514	515	518	3258	
Sep 21	7	565	38	157	360	497	554	529	419	240	48	35	35	35	35	35	35	35	122	5
	8	797	67	156	424	618	716	705	587	374	113	64	64	64	64	64	64	64	367	4
	9	887	87	114	335	547	665	684	602	424	181	90	86	86	86	86	86	86	585	3
	10	931	101	107	193	372	507	560	529	415	240	111	103	101	101	101	101	101	752	2
	11	952	111	114	118	169	272	356	389	361	279	176	118	114	111	111	111	111	856	1
	12	958	114	114	116	118	121	153	217	272	293	272	217	153	121	118	116	114	889	12
HALF-DAY TOTALS			461	712	1500	2276	2791	2937	2658	1963	1007	605	501	466	457	455	454	454	3126	
Oct 21	7	524	25	56	249	404	492	502	437	300	105	27	25	25	25	25	25	25	79	5
	8	816	55	64	299	548	702	747	677	502	234	59	55	55	55	55	55	55	313	4
	9	920	76	80	204	473	659	741	711	573	336	97	76	76	76	76	76	76	537	3
	10	968	92	94	108	291	499	621	647	577	412	189	97	92	92	92	92	92	707	2
	11	991	102	105	122	261	420	515	528	459	315	154	106	102	102	102	102	102	814	1
	12	997	105	105	105	107	111	189	330	437	474	437	330	189	111	107	105	105	850	12
HALF-DAY TOTALS			402	444	1002	1869	2637	3110	3141	2689	1776	891	553	428	404	402	402	402	2872	
Nov 21	7	423	17	19	134	280	375	406	379	289	147	19	17	17	17	17	17	17	43	5
	8	806	46	49	174	456	651	742	719	583	350	78	46	46	46	46	46	46	247	4
	9	929	67	67	105	382	623	779	779	679	472	180	70	67	67	67	67	67	468	3
	10	984	83	83	87	210	470	651	727	694	554	316	98	83	83	83	83	83	635	2
	11	1009	92	92	92	98	242	462	607	654	603	455	234	98	92	92	92	92	740	1
	12	1016	96	96	96	96	101	227	432	572	619	572	432	227	101	96	96	96	775	12
HALF-DAY TOTALS			352	357	620	1438	2363	3101	3396	3159	2421	1324	664	404	355	352	352	352	2520	
Dec 21	7	372	13	14	93	228	318	354	339	268	150	21	13	13	13	13	13	13	31	5
	8	803	42	43	129	416	625	734	728	609	390	105	42	42	42	42	42	42	219	4
	9	936	63	63	78	341	604	761	800	716	520	226	66	63	63	63	63	63	436	3
	10	993	78	78	81	178	445	657	753	735	605	369	112	79	78	78	78	78	602	2
	11	1019	87	87	87	92	231	474	638	698	654	506	270	94	87	87	87	87	704	1
	12	1026	91	91	91	91	95	241	469	620	670	620	469	241	95	91	91	91	739	12
HALF-DAY TOTALS			328	330	501	1269	2241	3076	3468	3312	2638	1527	721	393	331	328	328	328	2361	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.7 Solar Intensity and Solar Heat Gain Factors[a] for 32° N Latitude (SI units)[b]

			Solar Heat Gain Factors, W/m^2																	
Date	Solar Time A.M.	Direct Normal W/m^2	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time P.M.
Jan 21	7	4	0	0	1	3	4	4	4	3	2	0	0	0	0	0	0	0	0	5
	8	640	28	29	93	330	505	597	596	502	326	88	29	28	28	28	28	28	102	4
	9	849	48	48	53	286	553	721	775	711	534	258	52	48	48	48	48	48	278	3
	10	931	63	63	64	129	427	659	784	788	670	444	144	64	63	63	63	63	430	2
	11	967	71	71	71	75	213	502	698	784	750	602	347	90	71	71	71	71	524	1
	12	977	74	74	74	74	79	277	548	718	777	718	548	277	79	74	74	74	556	12
HALF-DAY TOTALS			249	250	338	897	1797	2700	3201	3198	2692	1746	831	353	252	249	249	249	1614	
Feb 21	7	352	13	23	148	258	323	336	299	212	83	14	13	13	13	13	13	13	30	5
	8	771	41	43	204	469	646	719	683	538	300	53	41	41	41	41	41	41	200	4
	9	905	60	60	101	386	627	764	783	680	471	174	63	60	60	60	60	60	402	3
	10	964	75	75	78	195	475	670	760	733	595	352	99	75	75	75	75	75	556	2
	11	990	83	83	83	88	240	491	656	717	670	519	275	89	83	83	83	83	652	1
	12	998	86	86	86	86	91	250	489	644	696	643	489	250	91	86	86	86	684	12
HALF-DAY TOTALS			314	324	635	1405	2318	3086	3408	3188	2461	1426	718	384	316	314	314	314	2181	
Mar 21	7	583	30	116	332	483	556	545	447	276	63	29	29	29	29	29	29	29	100	5
	8	821	54	78	339	576	717	746	661	473	195	57	54	54	54	54	54	54	315	4
	9	914	74	77	203	475	662	746	716	578	339	95	74	74	74	74	74	74	516	3
	10	959	88	88	96	273	499	637	677	615	456	221	93	88	88	88	88	88	667	2
	11	980	96	96	98	108	258	447	564	592	529	380	185	101	96	96	96	96	762	1
	12	987	99	99	99	99	105	209	386	511	554	511	386	209	105	99	99	99	795	12
HALF-DAY TOTALS			393	512	1131	1985	2761	3258	3284	2801	1858	1030	609	429	394	391	391	391	2757	
Apr 21	6	210	29	110	172	205	207	177	119	38	11	11	11	11	11	11	11	11	23	6
	7	649	53	253	462	593	631	575	428	204	49	45	45	45	45	45	45	45	191	5
	8	804	73	192	453	632	715	689	559	337	95	69	69	69	69	69	69	69	408	4
	9	876	89	113	324	532	649	669	591	418	183	92	87	87	87	87	87	87	593	3
	10	913	101	106	165	342	490	599	543	445	275	123	104	101	101	101	101	101	736	2
	11	932	109	109	115	149	263	371	426	415	340	222	126	113	109	109	109	109	825	1
	12	937	112	112	112	116	120	167	260	335	363	335	260	167	120	116	112	112	854	12
HALF-DAY TOTALS			508	932	1734	2500	3003	3129	2806	2033	1135	721	559	496	482	479	479	479	3203	
May 21	6	374	104	244	340	381	367	295	175	39	26	26	26	26	26	26	26	28	67	6
	7	666	112	350	535	638	643	550	374	134	60	57	57	57	57	57	57	59	256	5
	8	787	93	295	519	655	694	629	470	229	86	80	80	80	80	80	80	80	461	4
	9	849	104	194	404	558	625	601	488	294	117	100	97	97	97	97	97	97	633	3
	10	882	114	127	240	383	473	491	435	313	170	117	110	110	110	110	110	110	766	2
	11	898	121	124	132	186	260	312	322	285	215	147	126	122	118	118	118	118	847	1
	12	904	121	123	125	127	130	148	186	220	223	220	186	148	130	127	125	123	873	12
HALF-DAY TOTALS			700	1382	2214	2840	3106	2943	2356	1409	788	627	577	558	551	550	548	551	3464	
Jun 21	6	412	140	289	388	425	401	314	174	39	32	32	32	32	32	32	32	35	89	6
	7	662	148	384	556	644	634	529	342	109	62	62	62	62	62	62	62	65	279	5
	8	773	115	335	540	656	677	597	427	188	89	84	84	84	84	84	84	84	476	4
	9	831	110	234	431	563	609	567	440	244	111	101	101	101	101	101	101	101	642	3
	10	863	120	150	272	395	461	458	387	261	143	120	114	114	114	114	114	114	770	2
	11	880	126	130	148	202	258	288	280	237	177	135	128	125	122	122	122	122	847	1
	12	885	128	129	130	132	134	144	164	183	191	183	164	144	134	132	130	129	871	12
HALF-DAY TOTALS			824	1589	2403	2950	3108	2829	2137	1174	710	621	595	585	582	579	579	586	3538	
Jul 21	6	358	106	240	332	370	355	285	168	39	27	27	27	27	27	27	27	30	70	6
	7	640	118	349	526	623	626	534	361	129	62	59	59	59	59	59	59	61	257	5
	8	761	98	300	515	645	680	613	456	221	89	82	82	82	82	82	82	82	457	4
	9	823	107	202	405	553	615	588	475	284	117	100	100	100	100	100	100	100	626	3
	10	856	118	133	247	383	467	481	424	303	167	120	113	113	113	113	113	113	757	2
	11	873	124	128	137	191	261	308	314	277	210	147	129	125	121	121	121	121	836	1
	12	879	126	127	128	130	133	150	184	214	226	214	184	150	133	130	128	127	861	12
HALF-DAY TOTALS			728	1402	2210	2809	3052	2877	2290	1365	783	637	591	574	568	566	565	568	3431	
Aug 21	6	187	30	103	159	188	189	162	108	35	12	12	12	12	12	12	12	12	25	6
	7	599	59	250	444	565	598	542	402	192	53	49	49	49	49	49	49	49	192	5
	8	756	79	200	446	614	690	662	536	321	96	74	74	74	74	74	74	74	403	4
	9	830	95	124	328	523	632	648	570	402	179	98	93	93	93	93	93	93	583	3
	10	869	106	113	175	344	482	544	526	429	266	126	110	106	106	106	106	106	722	2
	11	889	115	117	122	157	264	365	414	401	328	217	131	119	115	115	115	115	808	1
	12	894	117	117	117	122	126	170	255	324	350	324	255	170	126	122	117	117	837	12
HALF-DAY TOTALS			539	957	1721	2443	2910	3014	2694	1950	1109	729	581	524	510	507	506	506	3152	
Sep 21	7	514	32	109	302	437	502	492	405	252	62	30	30	30	30	30	30	30	97	5
	8	758	57	81	324	546	679	706	626	450	190	61	57	57	57	57	57	57	304	4
	9	857	77	82	201	459	637	717	688	557	330	99	77	77	77	77	77	77	498	3
	10	905	91	91	101	270	485	617	655	596	444	220	97	91	91	91	91	91	645	2
	11	928	100	100	102	113	257	437	549	576	516	373	187	106	100	100	100	100	737	1
	12	935	103	103	103	103	110	210	379	499	540	499	379	210	110	103	103	103	769	12
HALF-DAY TOTALS			409	518	1089	1888	2621	3097	3132	2689	1812	1025	620	446	411	408	408	408	2664	
Oct 21	7	312	13	24	136	233	291	301	268	190	75	14	13	13	13	13	13	13	30	5
	8	724	42	46	200	450	616	684	649	511	285	54	42	42	42	42	42	42	198	4
	9	862	63	63	104	378	608	738	755	655	454	170	65	63	63	63	63	63	395	3
	10	923	77	77	81	197	465	652	737	711	577	342	101	77	77	77	77	77	546	2
	11	952	86	86	86	91	239	481	639	697	651	505	269	93	86	86	86	86	639	1
	12	960	89	89	89	89	95	247	478	626	677	626	278	247	95	89	89	89	671	12
HALF-DAY TOTALS			325	335	632	1365	2234	2968	3275	3067	2376	1390	714	394	328	325	325	325	2143	
Nov 21	7	5	0	0	1	3	4	5	4	3	2	0	0	0	0	0	0	0	0	5
	8	619	29	29	93	323	493	581	579	488	316	86	29	29	29	29	29	29	102	4
	9	829	49	49	55	284	545	709	761	697	523	253	49	49	49	49	49	49	277	3
	10	912	64	64	65	131	423	650	772	775	659	437	142	65	64	64	64	64	428	2
	11	949	72	72	72	76	213	496	688	773	739	593	342	91	72	72	72	72	521	1
	12	959	75	75	75	75	80	274	541	708	766	708	541	274	80	75	75	75	553	12
HALF-DAY TOTALS			253	254	342	890	1769	2653	3143	3138	2643	1717	824	355	256	253	253	253	607	
Dec 21	8	556	22	22	59	265	426	515	523	452	305	98	23	22	22	22	22	22	69	4
	9	812	43	43	46	244	512	686	751	701	539	282	48	43	43	43	43	43	228	3
	10	908	57	57	57	106	402	642	777	792	683	466	163	59	57	57	57	57	375	2
	11	949	66	66	66	69	200	497	700	795	766	620	367	92	66	66	66	66	468	1
	12	960	69	69	69	69	73	281	559	733	794	733	559	281	73	69	69	69	500	12
HALF-DAY TOTALS			223	223	265	717	1577	2499	3043	3111	2687	1823	868	339	225	223	223	223	1389	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.8 Solar Intensity and Solar Heat Gain Factors[a] for 40° N Latitude (SI units)[b]

Date	Solar Time A.M.	Direct Normal W/m^2	Solar Heat Gain Factors, W/m^2 N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time P.M.
Jan 21	8	446	17	17	55	223	350	417	420	358	236	60	17	17	17	17	17	17	44	4
	9	753	37	37	41	233	485	648	706	658	504	260	42	37	37	37	37	37	173	3
	10	865	51	51	51	97	390	627	761	776	671	460	161	53	51	51	51	51	303	2
	11	913	59	59	59	62	193	493	699	796	769	623	372	89	59	59	59	59	390	1
	12	926	62	62	62	62	66	293	563	740	802	740	563	283	62	62	62	62	419	12
HALF-DAY TOTALS			194	194	231	628	1426	2316	2852	2941	2566	1770	860	318	196	194	194	194	1117	
Feb 21	7	175	6	10	71	127	160	167	150	107	43	6	6	6	6	6	6	6	11	5
	8	692	33	35	158	407	576	651	628	505	296	56	33	33	33	33	33	33	136	4
	9	854	52	52	70	337	587	738	773	689	496	209	55	52	52	52	52	52	309	3
	10	926	65	65	67	155	450	666	777	768	641	408	120	66	65	65	65	65	451	2
	11	958	73	73	73	77	224	504	690	769	730	579	325	86	73	73	73	73	538	1
	12	967	76	76	76	76	80	271	536	702	760	702	536	271	80	76	76	76	568	12
HALF-DAY TOTALS			267	271	478	1140	2043	2888	3308	3202	2591	1602	790	361	269	267	267	267	1730	
Mar 21	7	540	27	92	295	441	514	509	425	271	69	26	26	26	26	26	26	26	83	5
	8	789	50	57	288	534	686	732	665	494	232	54	50	50	50	50	50	50	268	4
	9	889	67	70	147	429	640	749	744	625	404	127	69	67	67	67	67	67	450	3
	10	938	80	80	85	226	482	653	722	682	539	299	91	80	80	80	80	80	587	2
	11	961	88	88	88	94	247	476	623	673	622	473	244	94	88	88	88	85	673	1
	12	968	91	91	91	91	97	238	458	602	650	602	458	238	97	91	91	91	702	12
HALF-DAY TOTALS			358	440	954	1777	2626	3265	3429	3055	2191	1270	694	417	360	357	357	357	2411	
Apr 21	6	282	36	144	228	275	279	241	164	56	16	15	15	15	15	15	15	15	34	6
	7	651	50	223	442	584	633	588	451	255	51	45	45	45	45	45	45	45	193	5
	8	795	69	140	402	601	706	703	594	391	130	69	67	67	67	67	67	67	389	4
	9	865	84	91	254	488	638	691	640	494	260	91	84	84	84	84	84	84	557	3
	10	901	96	99	117	291	480	589	608	538	381	177	101	96	96	96	96	96	685	2
	11	920	104	107	107	122	255	411	506	522	459	323	164	109	104	104	104	104	766	1
	12	926	106	106	106	109	114	196	341	448	486	448	341	196	114	109	106	106	794	12
HALF-DAY TOTALS			487	835	1580	2390	3020	3314	3135	2466	1539	935	628	495	467	464	464	464	3020	
May 21	5	3	1	2	3	3	3	2	1	0	0	0	0	0	0	0	0	0	0	7
	6	453	113	284	403	458	446	364	223	56	33	33	33	33	33	33	33	35	96	6
	7	681	90	320	520	638	659	580	412	172	63	59	59	59	59	59	59	59	276	5
	8	787	86	230	471	629	694	655	519	295	92	80	80	80	80	80	80	80	461	4
	9	844	99	131	330	518	620	632	551	382	168	101	96	96	96	96	96	96	616	3
	10	875	107	114	171	332	467	529	513	419	262	127	111	107	107	107	107	107	737	2
	11	891	115	115	121	152	256	357	409	400	331	222	133	120	115	115	115	115	812	1
	12	896	117	117	117	121	126	171	258	329	355	329	258	171	126	121	117	117	836	12
HALF-DAY TOTALS			679	1275	2102	2818	3231	3232	2778	1897	1129	780	630	568	554	550	550	552	3418	
Jun 21	5	68	32	54	68	70	63	46	20	5	4	4	4	4	4	4	4	7	8	7
	6	488	150	329	450	501	478	380	222	53	39	39	39	39	39	39	39	43	126	6
	7	681	118	355	543	648	654	562	385	145	68	65	65	65	65	65	65	67	306	5
	8	776	94	268	492	633	680	626	480	252	93	85	85	85	85	85	85	85	484	4
	9	829	105	160	359	524	607	601	507	332	142	104	100	100	100	100	100	100	633	3
	10	859	112	121	197	345	457	500	468	366	218	122	115	112	112	112	112	112	750	2
	11	874	119	123	128	166	254	332	367	347	279	188	130	124	119	119	119	119	821	1
	12	879	121	121	121	127	131	163	227	281	301	281	227	163	131	127	121	121	844	12
HALF-DAY TOTALS			799	1483	2314	2968	3275	3151	2580	1649	995	743	642	602	592	588	587	594	3551	
Jul 21	5	7	3	5	7	7	6	5	2	0	0	0	0	0	0	0	0	1	1	7
	6	435	116	281	395	447	433	352	216	55	34	34	34	34	34	34	34	37	100	6
	7	656	95	321	513	625	643	564	400	166	66	62	62	62	62	62	62	62	278	5
	8	762	90	236	468	620	680	639	505	285	94	83	83	83	83	83	83	83	459	4
	9	818	102	138	333	513	610	618	537	371	165	104	99	99	99	99	99	99	611	3
	10	850	110	118	177	333	462	519	501	407	255	129	114	110	110	110	110	110	729	2
	11	866	117	120	125	157	256	352	400	389	321	217	135	123	117	117	117	117	802	1
	12	871	120	120	120	125	130	172	253	320	345	320	253	172	130	125	120	120	826	12
HALF-DAY TOTALS			705	1296	2102	2792	3180	3164	2707	1842	1110	783	643	586	572	568	567	570	3395	
Aug 21	6	255	38	137	214	256	259	223	151	52	18	17	17	17	17	17	17	17	38	6
	7	603	55	223	426	557	602	557	426	222	55	49	49	49	49	49	49	49	196	5
	8	747	75	149	397	584	681	676	569	374	128	74	72	72	72	72	72	72	386	4
	9	819	89	97	259	481	621	669	618	475	251	97	89	89	89	89	89	89	549	3
	10	857	102	105	126	294	472	574	590	519	567	173	107	102	102	102	102	102	674	2
	11	876	109	109	113	130	257	403	492	505	443	313	165	116	109	109	109	109	753	1
	12	882	112	112	112	115	120	197	333	434	470	434	333	197	120	115	112	112	780	12
HALF-DAY TOTALS			518	861	1571	2338	2929	3196	3015	2370	1496	932	647	524	496	492	492	492	2983	
Sep 21	7	472	28	87	265	395	460	456	381	244	66	27	27	27	27	27	27	27	80	5
	8	725	52	61	275	504	646	689	626	467	224	57	52	52	52	52	52	52	258	4
	9	830	71	73	148	413	613	717	712	599	391	129	73	71	71	71	71	71	434	3
	10	882	84	84	89	224	468	631	697	659	522	293	96	84	84	84	84	84	567	2
	11	906	92	92	92	99	245	463	604	652	603	461	242	99	92	92	92	92	651	1
	12	914	95	95	95	95	101	237	446	584	631	584	446	237	101	95	95	95	679	12
HALF-DAY TOTALS			374	447	917	1683	2484	3092	3257	2918	2119	1250	699	432	376	373	373	373	2329	
Oct 21	7	153	6	10	64	113	142	148	132	94	38	7	6	6	6	6	6	38	12	5
	8	644	35	37	155	387	545	615	592	476	280	56	35	35	35	35	35	35	136	4
	9	811	54	54	73	329	567	710	743	661	476	202	57	54	54	54	54	54	305	3
	10	884	67	67	70	157	439	646	752	742	619	395	120	69	67	67	67	67	443	2
	11	917	76	76	76	80	223	491	670	745	707	562	317	89	76	76	76	76	529	1
	12	927	78	78	78	78	84	267	521	681	737	681	521	267	84	78	78	78	558	12
HALF-DAY TOTALS			277	282	479	1106	1965	2771	3173	3074	2494	555	780	369	280	277	277	277	1704	
Nov 21	8	430	17	17	55	217	339	404	406	346	228	66	18	17	17	17	17	17	44	4
	9	733	38	38	42	231	476	634	691	643	492	254	43	38	38	38	38	38	173	3
	10	846	52	52	52	99	385	617	748	763	659	145	159	54	52	52	52	52	303	2
	11	894	60	60	60	63	192	486	688	783	757	613	367	89	60	60	60	60	388	1
	12	908	63	63	63	63	67	280	555	728	789	728	555	280	67	63	63	63	418	12
HALF-DAY TOTALS			197	198	235	623	1403	2273	2797	2884	2516	1738	850	319	199	197	197	197	1115	
Dec 21	8	279	9	9	25	129	212	259	264	230	157	52	10	9	9	9	9	9	20	4
	9	685	31	31	33	188	427	584	646	611	477	260	40	31	31	31	31	31	124	3
	10	825	45	45	45	78	358	594	732	755	661	462	173	47	45	45	45	45	244	2
	11	882	53	53	53	55	177	477	685	786	765	624	379	90	53	53	53	53	327	1
	12	898	56	56	56	56	60	281	560	736	798	738	560	281	60	56	56	56	356	12
HALF-DAY TOTALS			165	165	178	461	1180	2046	2594	2736	2446	1757	870	298	167	165	165	165	891	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.9 Solar Intensity and Solar Heat Gain Factors[a] for 48° N Latitude (SI units)[b]

Date	Solar Time A.M.	Direct Normal W/m²	Solar Heat Gain Factors, W/m²																	Solar Time P.M.
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	
Jan 21	8	116	4	4	13	57	90	109	110	94	63	18	4	4	4	4	4	4	7	4
	9	584	24	24	26	168	371	505	555	523	406	217	30	24	24	24	24	24	79	3
	10	754	37	37	37	69	333	554	682	702	615	429	159	39	37	37	37	37	174	2
	11	823	45	45	45	47	166	455	656	753	734	598	365	83	45	45	45	45	244	1
	12	842	48	48	48	48	51	271	541	713	772	713	541	271	51	48	48	48	269	12
	HALF-DAY TOTALS		134	134	144	368	996	1788	2298	2448	2212	1616	817	267	136	134	134	134	639	
Feb 21	7	11	0	1	5	8	10	11	10	7	0	0	0	0	0	0	0	0	1	5
	8	568	24	25	114	324	470	537	524	428	259	52	24	24	24	24	24	24	78	4
	9	780	42	42	49	284	530	683	727	660	488	225	45	42	42	42	42	42	210	3
	10	869	54	54	55	120	415	641	764	768	653	434	137	55	54	54	54	54	331	2
	11	908	61	61	61	64	205	498	696	787	755	607	355	84	61	61	61	61	409	1
	12	920	63	63	63	63	68	280	555	728	790	728	555	280	68	63	63	63	435	12
	HALF-DAY TOTALS		214	216	337	864	1708	2575	3054	3051	2565	1677	825	328	216	214	214	214	1246	
Mar 21	7	482	23	71	253	387	458	458	388	253	71	23	22	22	22	22	22	22	64	5
	8	744	44	48	239	486	644	701	651	498	257	49	44	44	44	44	44	44	214	4
	9	853	60	60	104	381	609	738	753	652	449	164	62	60	60	60	60	60	371	3
	10	906	72	72	75	183	460	656	749	728	596	363	104	72	72	72	72	72	493	2
	11	932	79	79	79	83	232	492	663	731	689	541	297	88	79	79	79	79	568	1
	12	939	81	81	81	81	86	261	509	666	720	666	509	261	86	81	81	81	594	12
	HALF-DAY TOTALS		317	372	790	1558	2446	3193	3471	3199	2420	1466	769	399	319	316	316	316	2006	
Apr 21	6	340	39	167	271	330	337	294	203	74	20	19	19	19	19	19	19	19	46	6
	7	646	49	191	417	567	628	595	468	264	56	45	45	45	45	45	45	45	189	5
	8	779	64	99	350	566	690	709	619	435	173	67	64	64	64	64	64	64	359	4
	9	847	79	83	191	444	621	703	679	554	335	105	79	79	79	79	79	79	507	3
	10	884	90	90	97	244	466	610	660	613	472	251	97	90	90	90	90	90	618	2
	11	902	97	97	97	105	245	443	570	609	558	419	217	103	97	97	97	97	689	1
	12	908	99	99	99	99	106	224	414	543	587	543	414	224	106	99	99	99	713	12
	HALF-DAY TOTALS		463	765	1454	2285	3019	3465	3411	2825	1908	1169	713	492	445	442	442	442	2761	
May 21	5	129	52	97	125	133	122	91	44	9	8	8	8	8	8	8	8	10	16	7
	6	511	112	305	443	512	504	418	267	75	38	38	38	38	38	38	38	40	125	6
	7	690	73	283	498	631	668	604	448	214	66	61	61	61	61	61	61	61	287	5
	8	782	83	170	418	599	689	675	562	358	120	79	79	79	79	79	79	79	449	4
	9	834	93	101	259	475	611	656	605	463	243	100	93	93	93	93	93	93	585	3
	10	864	103	106	124	283	458	561	579	513	366	179	109	103	103	103	103	103	690	2
	11	879	109	109	113	127	249	396	488	505	447	320	170	116	109	109	109	109	756	1
	12	884	111	111	111	114	120	198	336	439	474	439	336	198	120	114	111	111	778	12
	HALF-DAY TOTALS		679	1224	2035	2817	3360	3515	3176	2363	1525	997	709	579	550	546	546	549	3297	
Jun 21	5	243	111	192	241	252	228	166	75	19	17	17	17	17	17	17	17	24	38	7
	6	544	146	348	488	552	534	434	266	70	46	46	46	46	46	46	46	49	162	6
	7	693	93	317	521	642	467	591	427	188	72	67	67	67	67	67	67	67	324	5
	8	775	90	203	440	604	678	651	529	320	107	84	84	84	84	84	84	84	479	4
	9	822	98	114	286	482	600	629	567	418	208	105	98	98	98	98	98	98	610	3
	10	849	108	113	142	296	450	534	540	465	319	157	114	108	108	108	108	108	711	2
	11	864	114	114	120	138	248	373	449	456	396	279	156	121	114	114	114	114	775	1
	12	869	116	116	116	120	126	189	303	391	423	391	303	189	126	120	116	116	796	12
	HALF-DAY TOTALS		811	1446	2279	3013	3454	3477	3013	2140	1376	942	718	620	597	593	592	602	3495	
Jul 21	5	135	57	104	133	141	129	96	46	11	9	9	9	9	9	9	9	12	18	7
	6	492	116	302	436	501	492	407	259	75	40	40	40	40	40	40	40	43	130	6
	7	666	78	285	492	619	653	588	436	207	69	63	63	63	63	63	63	63	290	5
	8	757	86	176	416	590	675	660	547	348	119	81	81	81	81	81	81	81	448	4
	9	809	96	106	263	471	601	643	591	450	237	104	96	96	96	96	96	96	582	3
	10	839	106	109	130	285	453	550	566	500	356	177	112	106	106	106	106	106	684	2
	11	855	112	112	117	132	249	390	477	492	435	312	169	119	112	112	112	112	749	1
	12	859	114	114	114	117	124	198	329	428	462	428	329	198	124	117	114	114	771	12
	HALF-DAY TOTALS		705	1247	2039	2795	3311	3446	3101	2303	1496	993	721	598	570	565	565	569	3287	
Aug 21	6	311	42	161	256	310	316	273	190	70	22	21	21	21	21	21	21	21	51	6
	7	599	53	193	403	543	598	565	444	250	59	49	49	49	49	49	49	49	193	5
	8	732	69	108	347	549	665	681	593	417	168	73	69	69	69	69	69	69	358	4
	9	801	84	90	198	437	605	681	655	534	323	108	84	84	84	84	84	84	502	3
	10	839	95	95	104	247	453	593	639	592	456	245	104	95	95	95	95	95	610	2
	11	858	102	102	102	112	247	433	553	589	539	406	215	110	102	102	102	102	679	1
	12	864	104	104	104	104	113	224	404	526	568	526	404	224	113	104	104	104	702	12
	HALF-DAY TOTALS		496	790	1449	2237	2929	3343	3282	2720	1852	1156	728	521	475	471	471	471	2741	
Sep 21	7	414	24	66	224	342	403	403	342	224	66	24	23	23	23	23	23	23	62	5
	8	678	46	51	228	455	602	654	608	467	244	52	46	46	46	46	46	46	206	4
	9	792	63	63	107	366	581	702	716	621	430	163	66	63	63	63	63	63	358	3
	10	848	75	75	79	182	444	630	719	699	573	353	107	75	75	75	75	75	476	2
	11	876	82	82	82	88	230	476	639	704	664	524	292	93	82	82	82	82	549	1
	12	884	84	84	84	84	91	257	494	643	695	643	494	257	91	84	84	84	574	12
	HALF-DAY TOTALS		332	381	758	1467	2300	3007	3280	3039	2324	1429	766	334	331	331	331	1937		
Oct 21	7	12	0	1	5	9	11	12	11	8	3	0	0	0	0	0	0	0	1	5
	8	522	25	27	111	304	439	501	489	398	242	51	25	25	25	25	25	25	79	4
	9	734	44	44	52	276	508	652	693	629	466	216	47	44	44	44	44	44	208	3
	10	825	56	56	58	122	403	618	736	739	628	418	136	58	56	56	56	56	327	2
	11	866	64	64	64	67	203	483	673	760	729	587	345	86	64	64	64	64	403	1
	12	878	66	66	66	66	71	274	538	704	763	704	538	274	71	66	66	66	429	12
	HALF-DAY TOTALS		223	225	340	838	1637	2461	2918	2918	2459	1619	808	334	226	223	223	223	1233	
Nov 21	8	115	4	4	13	57	90	108	109	93	62	18	4	4	4	4	4	4	7	4
	9	565	25	25	27	165	363	492	540	509	394	211	31	25	25	25	25	25	81	3
	10	735	38	38	38	70	328	543	668	688	602	420	156	40	38	38	38	38	175	2
	11	804	46	46	46	48	165	448	645	739	720	587	358	83	46	46	46	46	244	1
	12	823	48	48	48	48	53	267	531	700	758	700	531	267	53	48	48	48	269	12
	HALF-DAY TOTALS		138	138	147	368	979	1752	2250	2396	2165	1583	804	268	140	138	138	138	642	
Dec 21	9	442	16	16	18	113	272	378	420	401	316	176	25	16	16	16	16	16	42	3
	10	676	30	30	30	51	286	491	613	636	563	398	156	32	30	30	30	30	119	2
	11	765	38	38	38	40	146	421	615	708	694	569	351	80	38	38	38	38	181	1
	12	789	41	41	41	41	44	256	514	679	734	679	514	256	44	41	41	41	204	12
	HALF-DAY TOTALS		105	105	107	231	735	1444	1924	2098	1944	1477	778	239	107	105	105	105	444	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.10 Solar Intensity and Solar Heat Gain Factors[a] for 64° N Latitude (SI units)[b]

Date	Solar Time A.M.	Direct Normal W/m²	Solar Heat Gain Factors, W/m² N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time P.M.
Jan 21	10	69	2	2	2	4	29	51	63	66	58	41	16	2	2	2	2	2	4	2
	11	256	9	9	9	9	46	143	210	242	238	196	120	24	9	9	9	9	18	1
	12	316	11	11	11	11	12	104	211	280	302	280	211	104	12	11	11	11	24	12
HALF-DAY TOTALS			16	16	16	18	80	250	382	449	446	374	237	72	17	16	16	16	33	
Feb 21	8	56	2	2	9	31	46	53	53	44	27	6	2	2	2	2	2	2	3	4
	9	422	16	16	18	136	280	373	403	375	285	143	18	16	16	16	16	16	41	3
	10	601	26	26	26	57	276	453	554	567	495	341	119	28	26	26	26	26	90	2
	11	679	32	32	32	34	139	386	558	638	622	506	307	64	32	32	32	32	128	1
	12	701	34	34	34	34	37	231	464	613	662	613	464	231	37	34	34	34	143	12
HALF-DAY TOTALS			93	93	103	279	770	1408	1822	1947	1767	1298	668	210	95	93	93	93	334	
Mar 21	7	300	12	34	147	235	284	288	249	168	54	13	12	12	12	12	12	12	27	5
	8	582	29	31	147	357	499	559	536	427	246	44	29	29	29	29	29	29	100	4
	9	717	41	41	51	277	502	642	679	613	450	203	44	41	41	41	41	41	187	3
	10	786	49	49	50	111	386	598	714	719	613	410	132	51	49	49	49	49	264	2
	11	821	54	54	54	57	190	468	658	746	718	579	344	80	54	54	54	54	314	1
	12	831	56	56	56	56	61	269	530	696	754	696	530	269	61	56	56	56	331	12
HALF-DAY TOTALS			213	234	473	1052	1879	2695	3103	3021	2457	1591	811	330	215	213	213	213	1057	
Apr 21	5	85	24	56	77	85	81	64	36	6	4	4	4	4	4	4	4	5	8	7
	6	419	38	187	320	400	416	371	266	111	26	24	24	24	24	24	24	24	67	6
	7	613	43	129	355	516	595	584	482	303	80	41	41	41	41	41	41	41	162	5
	8	720	54	60	249	483	633	685	634	484	250	60	54	54	54	54	54	54	269	4
	9	783	65	65	100	351	567	691	710	620	436	174	68	65	65	65	65	65	367	3
	10	820	72	72	76	161	421	613	709	698	582	372	119	74	72	72	72	72	441	2
	11	839	77	77	77	82	215	468	637	710	676	540	312	93	77	77	77	77	448	1
	12	846	79	79	79	79	85	262	503	655	708	655	503	262	85	79	79	79	504	12
HALF-DAY TOTALS			413	687	1294	2116	2974	3628	3741	3268	2408	1537	861	471	381	378	378	378	2053	
May 21	4	160	94	139	162	161	135	87	25	10	10	10	10	10	10	10	11	31	20	8
	5	416	152	298	393	425	395	302	158	34	29	29	29	29	29	29	29	33	81	7
	6	584	90	304	474	570	579	499	343	126	49	46	46	46	46	46	46	46	175	6
	7	688	65	199	436	596	665	634	507	297	78	60	60	60	60	60	60	60	284	5
	8	754	72	89	307	527	660	694	623	459	215	78	72	72	72	72	72	72	390	4
	9	796	82	85	143	384	577	678	679	579	389	147	85	82	82	82	82	82	481	3
	10	822	89	89	94	193	427	593	668	645	528	322	114	89	89	89	89	89	549	2
	11	836	93	93	93	100	226	446	594	652	614	485	275	105	93	93	93	93	592	1
	12	841	95	95	95	95	103	248	460	597	644	597	460	248	103	95	95	95	606	12
HALF-DAY TOTALS			780	1341	2145	2998	3712	4073	3841	3108	2234	1467	909	603	533	529	530	554	2875	
Jun 21	4	294	181	263	302	297	247	156	43	21	21	21	21	21	21	21	23	67	50	8
	5	485	195	360	466	498	458	346	175	44	39	39	39	39	39	39	39	45	124	7
	6	614	113	338	510	603	605	516	347	122	57	55	55	55	55	55	55	57	223	6
	7	698	74	225	457	610	672	632	498	282	80	68	68	68	68	68	68	68	331	5
	8	754	79	105	327	535	657	682	605	438	197	85	79	79	79	79	79	79	433	4
	9	791	89	93	161	393	572	862	655	552	362	137	92	89	89	89	89	89	520	3
	10	814	96	96	102	205	423	577	642	615	497	297	114	96	96	96	96	96	585	2
	11	827	100	100	100	108	228	431	568	619	581	456	258	110	100	100	100	100	627	1
	12	831	101	101	101	101	110	240	436	566	610	566	436	240	110	101	101	101	641	12
HALF-DAY TOTALS			1016	1080	2526	3347	3953	4154	3769	2985	2142	1436	935	667	605	601	603	673	3219	
Jul 21	4	168	101	149	173	172	144	93	27	12	12	12	12	12	12	12	12	35	24	8
	5	405	154	297	389	420	390	298	156	36	32	32	32	32	32	32	32	36	88	7
	6	564	94	303	467	560	567	488	335	124	51	49	49	49	49	49	49	49	181	6
	7	665	69	201	431	585	652	620	495	290	80	63	63	63	63	63	63	63	289	5
	8	730	75	94	307	520	648	680	609	449	211	81	75	75	75	75	75	75	393	4
	9	771	85	88	148	382	567	665	664	566	380	146	88	85	85	85	85	85	481	3
	10	797	92	92	98	196	422	583	655	631	516	315	116	92	92	92	92	92	548	2
	11	812	96	96	96	104	226	439	582	638	601	475	271	108	96	96	96	96	590	1
	12	816	98	98	98	98	107	246	452	585	630	585	452	246	107	98	98	98	604	12
HALF-DAY TOTALS			814	1370	2157	2985	3669	4004	3763	3046	2198	1457	920	626	557	553	554	582	2985	
Aug 21	5	92	28	62	85	94	89	71	40	8	6	6	6	6	6	6	6	6	11	7
	6	388	42	182	306	380	395	352	252	107	30	27	27	27	27	27	27	27	73	6
	7	570	48	132	344	494	567	555	458	289	81	45	45	45	45	45	45	45	168	5
	8	675	59	66	247	468	609	657	607	464	241	66	59	59	59	59	59	59	273	4
	9	737	70	70	107	345	549	666	683	597	420	172	74	70	70	70	70	70	368	3
	10	775	78	78	82	165	412	594	685	674	562	361	122	80	78	78	78	78	440	2
	11	794	82	82	82	89	216	456	617	686	653	523	305	99	82	82	82	82	485	1
	12	801	84	84	84	84	92	260	489	635	684	633	489	260	92	84	84	84	501	12
HALF-DAY TOTALS			447	714	1293	2073	2884	3498	3600	3147	2333	1509	869	500	413	409	409	410	2069	
Sep 21	7	242	12	30	122	194	234	238	206	139	47	13	12	12	12	12	12	12	26	5
	8	513	30	33	136	324	451	505	484	387	225	45	30	30	30	30	30	30	97	4
	9	651	43	43	54	261	468	596	631	570	420	193	47	43	43	43	43	43	181	3
	10	722	52	52	53	111	366	563	672	677	577	388	131	54	52	52	52	52	255	2
	11	758	57	57	57	61	185	445	623	706	680	549	329	83	57	57	57	57	303	1
	12	769	59	59	59	59	65	260	504	660	715	660	504	260	65	59	59	59	320	12
HALF-DAY TOTALS			224	241	448	968	1727	2484	2871	2810	2305	1513	787	336	227	224	224	224	1021	
Oct 21	8	54	2	2	10	30	45	52	51	42	26	6	2	2	2	2	2	2	4	4
	9	383	17	17	19	127	259	345	372	346	263	133	19	17	17	17	17	17	42	3
	10	556	28	28	28	58	261	426	520	532	465	321	115	29	28	28	28	28	91	2
	11	633	34	34	34	36	135	367	528	603	588	479	292	64	34	34	34	34	130	1
	12	655	36	36	36	36	40	222	441	581	628	581	441	222	40	36	36	36	144	12
HALF-DAY TOTALS			98	98	109	273	728	1324	1711	1829	1661	1225	638	209	100	98	98	98	339	
Nov 21	10	72	2	2	2	5	31	53	67	69	62	43	17	3	2	2	2	2	4	2
	11	250	9	9	9	10	46	140	207	238	234	192	118	24	9	9	9	9	19	1
	12	307	11	11	11	11	13	102	207	274	295	274	207	102	13	11	11	11	25	12
HALF-DAY TOTALS			17	17	17	19	81	248	378	444	440	369	234	71	18	17	17	17	35	
Dec 21	11	12	0	0	0	0	2	7	10	12	11	9	6	1	0	0	0	0	1	1
	12	51	1	1	1	1	2	16	34	45	48	45	34	16	2	1	1	1	3	12
HALF-DAY TOTALS			1	1	1	1	3	16	28	35	36	32	22	8	1	1	1	1	2	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half-day totals computed by Simpson's rule, time interval = 10 minutes.

TABLE C.11 Solar Position and Clear-Day Insolation, 32° N Latitude (I-P units)

	Solar Time		Solar Position				Global Irradiance (Btu/h ft^2)				
								South-Facing Elevation Angle			
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jan 21	7	5	1.4	65.2	1	0	0	0	0	1	1
	8	4	12.5	56.5	203	56	93	106	116	123	115
	9	3	22.5	46.0	269	118	175	193	206	212	181
	10	2	30.6	33.1	295	167	235	256	269	274	221
	11	1	36.1	17.5	306	198	273	295	308	312	245
	12		38.0	0.0	310	209	285	308	321	324	253
			Surface Daily Totals		2458	1288	1839	2008	2118	2166	1779
Feb 21	7	5	7.1	73.5	121	22	34	37	40	42	38
	8	4	19.0	64.4	247	95	127	136	140	141	108
	9	3	29.9	53.4	288	161	206	217	222	220	158
	10	2	39.1	39.4	306	212	266	278	283	279	193
	11	1	45.6	21.4	315	244	304	317	321	315	214
	12		48.0	0.0	317	255	316	330	334	328	222
			Surface Daily Totals		2872	1724	2188	2300	2345	2322	1644
Mar 21	7	5	12.7	81.9	185	54	60	60	59	56	32
	8	4	25.1	73.0	260	129	146	147	144	137	78
	9	3	36.8	62.1	290	194	222	224	220	209	119
	10	2	47.3	47.5	304	245	280	283	278	265	150
	11	1	55.0	26.8	311	277	317	321	315	300	170
	12		58.0	0.0	313	287	329	333	327	312	177
			Surface Daily Totals		3012	2084	2378	2403	2358	2246	1276
Apr 21	6	6	6.1	99.9	66	14	9	6	6	5	3
	7	5	18.8	92.2	206	86	78	71	62	51	10
	8	4	31.5	84.0	255	158	156	148	136	120	35
	9	3	43.9	74.2	278	220	225	217	203	183	68
	10	2	55.7	60.3	290	267	279	272	256	234	95
	11	1	65.4	37.5	295	297	313	306	290	265	112
	12		69.6	0.0	297	307	325	318	301	276	118
			Surface Daily Totals		3076	2390	2444	2356	2206	1994	764
May 21	6	6	10.4	107.2	119	36	21	13	13	12	7
	7	5	22.8	100.1	211	107	88	75	60	44	13
	8	4	35.4	92.9	250	175	159	145	127	105	15
	9	3	48.1	84.7	269	233	223	209	188	163	33
	10	2	60.6	73.3	280	277	273	259	237	208	56
	11	1	72.0	51.9	285	305	305	290	268	237	72
	12		78.0	0.0	286	315	315	301	278	247	77
			Surface Daily Totals		3112	2582	2454	2284	2064	1788	469
Jun 21	6	6	12.2	110.2	131	45	26	16	15	14	9
	7	5	24.3	103.4	210	115	91	76	59	41	14
	8	4	36.9	96.8	245	180	159	143	122	99	16
	9	3	49.6	89.4	264	236	221	204	181	153	19
	10	2	62.2	79.7	274	279	268	251	227	197	41
	11	1	74.2	60.9	279	306	299	282	257	224	56
	12		81.5	0.0	280	315	309	292	267	234	60
			Surface Daily Totals		3084	2634	2436	2234	1990	1690	370

TABLE C.11 Solar Position and Clear-Day Insolation, 32° N Latitude (I-P units) (*Continued*)

	Solar Time		Solar Position				Global Irradiance (Btu/h ft^2)					
								South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jul 21	6	6	10.7	107.7	113	37	22	14	13	12	8
	7	5	23.1	100.6	203	107	87	75	60	44	14
	8	4	35.7	93.6	241	174	158	143	125	104	16
	9	3	48.4	85.5	261	230	220	205	185	159	31
	10	2	60.9	74.3	271	274	269	254	232	204	54
	11	1	72.4	53.3	277	302	300	285	262	232	69
	12		78.6	0.0	279	311	310	296	273	242	74
			Surface Daily Totals		3012	2558	2422	2250	2030	1754	458
Aug 21	6	6	6.5	100.5	59	14	9	7	6	6	4
	7	5	19.1	92.8	190	85	77	69	60	50	12
	8	4	31.8	84.7	240	156	152	144	132	116	33
	9	3	44.3	75.0	263	216	220	212	197	178	65
	10	2	56.1	61.3	276	262	272	264	249	226	91
	11	1	66.0	38.4	282	292	305	298	281	257	107
	12		70.3	0.0	284	302	317	309	292	268	113
			Surface Daily Totals		2902	2352	2388	2296	2144	1934	736
Sep 21	7	5	12.7	81.9	163	51	56	56	55	52	30
	8	4	25.1	73.0	240	124	140	141	138	131	75
	9	3	36.8	62.1	272	188	213	215	211	201	114
	10	2	47.3	47.5	287	237	270	273	268	255	145
	11	1	55.0	26.8	294	268	306	309	303	289	164
	12		58.0	0.0	296	278	318	321	315	300	171
			Surface Daily Totals		2808	2014	2288	2308	2264	2154	1226
Oct 21	7	5	6.8	73.1	99	19	29	32	34	36	32
	8	4	18.7	64.0	229	90	120	128	133	134	104
	9	3	29.5	53.0	273	155	198	208	213	212	153
	10	2	38.7	39.1	293	204	257	269	273	270	188
	11	1	45.1	21.1	302	236	294	307	311	306	209
	12		47.5	0.0	304	247	306	320	324	318	217
			Surface Daily Totals		2696	1654	2100	2208	2252	2232	1588
Nov 21	7	5	1.5	65.4	2	0	0	0	1	1	1
	8	4	12.7	56.6	196	55	91	104	113	119	111
	9	3	22.6	46.1	263	118	173	190	202	208	176
	10	2	30.8	33.2	289	166	233	252	265	270	217
	11	1	36.2	17.6	301	197	270	291	303	307	241
	12		38.2	0.0	304	207	282	304	316	320	249
			Surface Daily Totals		2406	1280	1816	1980	2084	2130	1742
Dec 21	8	4	10.3	53.8	176	41	77	90	101	108	107
	9	3	19.8	43.6	257	102	161	180	195	204	183
	10	2	27.6	31.2	288	150	221	244	259	267	226
	11	1	32.7	16.4	301	180	258	282	298	305	251
	12		34.6	0.0	304	190	271	295	311	318	259
			Surface Daily Totals		2348	1136	1704	1888	2016	2086	1794

Source: Reprinted by permission from Peter J. Lunde, *Solar Thermal Engineering*, © 1980, John Wiley & Sons, New York.

TABLE C.12 Solar Position and Clear-Day Insolation, 40° N Latitude (I-P units)

Date	Solar Time A.M.	Solar Time P.M.	Solar Position Alt	Solar Position Azm	Direct Normal	Global Irradiance (Btu/h ft^2) Horiz	South-Facing Elevation Angle 22	32	42	52	90
Jan 21	8	4	8.1	55.3	142	28	65	74	81	85	84
	9	3	16.8	44.0	239	83	155	171	182	187	171
	10	2	23.8	30.9	274	127	218	237	249	254	223
	11	1	28.4	16.0	289	154	257	277	290	293	253
	12		30.0	0.0	294	164	270	291	303	306	263
			Surface Daily Totals		2182	948	1660	1810	1906	1944	1726
Feb 21	7	5	4.8	72.7	69	10	19	21	23	24	22
	8	4	15.4	62.2	224	73	114	122	126	127	107
	9	3	25.0	50.2	274	132	195	205	209	208	167
	10	2	32.8	35.9	295	178	256	267	271	267	210
	11	1	38.1	18.9	305	206	293	306	310	304	236
	12		40.0	0.0	308	216	306	319	323	317	245
			Surface Daily Totals		2640	1414	2060	2162	2202	2176	1730
Mar 21	7	5	11.4	80.2	171	46	55	55	54	51	35
	8	4	22.5	69.6	250	114	140	141	138	131	89
	9	3	32.8	57.3	282	173	215	217	213	202	138
	10	2	41.6	41.9	297	218	273	276	271	258	176
	11	1	47.7	22.6	305	247	310	313	307	293	200
	12		50.0	0.0	307	257	322	326	320	305	208
			Surface Daily Totals		2916	1852	2308	2330	2284	2174	1484
Apr 21	6	6	7.4	98.9	89	20	11	8	7	7	4
	7	5	18.9	89.5	206	87	77	70	61	50	12
	8	4	30.3	79.3	252	152	153	145	133	117	53
	9	3	41.3	67.2	274	207	221	213	199	179	93
	10	2	51.2	51.4	286	250	275	267	252	229	126
	11	1	58.7	29.2	292	277	308	301	285	260	147
	12		61.6	0.0	293	287	320	313	296	271	154
			Surface Daily Totals		3092	2274	2412	2320	2168	1956	1022
May 21	5	7	1.9	114.7	1	0	0	0	0	0	0
	6	6	12.7	105.6	144	49	25	15	14	13	9
	7	5	24.0	96.6	216	114	89	76	60	44	13
	8	4	35.4	87.2	250	175	158	144	125	104	25
	9	3	46.8	76.0	267	227	221	206	186	160	60
	10	2	57.5	60.9	277	267	270	255	233	205	89
	11	1	66.2	37.1	283	293	301	287	264	234	108
	12		70.0	0.0	284	301	312	297	274	243	114
			Surface Daily Totals		3160	2552	2442	2264	2040	1760	724
Jun 21	5	7	4.2	117.3	22	4	3	3	2	2	1
	6	6	14.8	108.4	155	60	30	18	17	16	10
	7	5	26.0	99.7	216	123	92	77	59	40	14
	8	4	37.4	90.7	246	182	159	142	121	97	16
	9	3	48.8	80.2	263	233	219	202	179	151	47
	10	2	59.8	65.8	272	272	266	248	224	193	74
	11	1	69.2	41.9	277	296	296	278	253	221	92
	12		73.5	0.0	279	304	306	289	263	230	98
			Surface Daily Totals		3180	2648	2434	2224	1974	1670	610

TABLE C.12 Solar Position and Clear-Day Insolation, 40° N Latitude (I-P units) (*Continued*)

	Solar Time		Solar Position				Global Irradiance (Btu/h ft^2)				
								South-Facing Elevation Angle			
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jul 21	5	7	2.3	115.2	2	0	0	0	0	0	0
	6	6	13.1	106.1	138	50	26	17	15	14	9
	7	5	24.3	97.2	208	114	89	75	60	44	14
	8	4	35.8	87.8	241	174	157	142	124	102	24
	9	3	47.2	76.7	259	225	218	203	182	157	58
	10	2	57.9	61.7	269	265	266	251	229	200	86
	11	1	66.7	37.9	275	290	296	281	258	228	104
	12		70.6	0.0	276	298	307	292	269	238	111
			Surface Daily Totals		3062	2534	2409	2230	2006	1728	702
Aug 21	6	6	7.9	99.5	81	21	12	9	8	7	5
	7	5	19.3	90.0	191	87	76	69	60	49	12
	8	4	30.7	79.9	237	150	150	141	129	113	50
	9	3	41.8	67.9	260	205	216	207	193	173	89
	10	2	51.7	52.1	272	246	267	259	244	221	120
	11	1	59.3	29.7	278	273	300	292	276	252	140
	12		62.3	0.0	280	282	311	303	287	262	147
			Surface Daily Totals		2916	2244	2354	2258	2104	1894	978
Sep 21	7	5	11.4	80.2	149	43	51	51	49	47	32
	8	4	22.5	69.6	230	109	133	134	131	124	84
	9	3	32.8	57.3	263	167	206	208	203	193	132
	10	2	41.6	41.9	280	211	262	265	260	247	168
	11	1	47.7	22.6	287	239	298	301	295	281	192
	12		50.0	0.0	290	249	310	313	307	292	200
			Surface Daily Totals		2708	1788	2210	2228	2182	2074	1416
Oct 21	7	5	4.5	72.3	48	7	14	15	17	17	16
	8	4	15.0	61.9	204	68	106	113	117	118	100
	9	3	24.5	49.8	257	126	185	195	200	198	160
	10	2	32.4	35.6	280	170	245	257	261	257	203
	11	1	37.6	18.7	291	199	283	295	299	294	229
	12		39.5	0.0	294	208	295	308	312	306	238
			Surface Daily Totals		2454	1348	1962	2060	2098	2074	1654
Nov 21	8	4	8.2	55.4	136	28	63	72	78	82	81
	9	3	17.0	44.1	232	82	152	167	178	183	167
	10	2	24.0	31.0	268	126	215	233	245	249	219
	11	1	28.6	16.1	283	153	254	273	285	288	248
	12		30.2	0.0	288	163	267	287	298	301	258
			Surface Daily Totals		2128	942	1636	1778	1870	1908	1686
Dec 21	8	4	5.5	53.0	89	14	39	45	50	54	56
	9	3	14.0	41.9	217	65	135	152	164	171	163
	10	2	20.7	29.4	261	107	200	221	235	242	221
	11	1	25.0	15.2	280	134	239	262	276	283	252
	12		26.6	0.0	285	143	253	275	290	296	263
			Surface Daily Totals		1978	782	1480	1634	1740	1796	1646

Source: Reprinted by permission from Peter J. Lunde, *Solar Thermal Engineering*, © 1980, John Wiley & Sons, New York.

TABLE C.13 Solar Position and Clear-Day Insolation, 48° N Latitude (I-P units)

	Solar Time		Solar Position			Global Irradiance (Btu/h ft^2)					
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jan 21	8	4	3.5	54.6	37	4	17	19	21	22	22
	9	3	11.0	42.6	185	46	120	132	140	145	139
	10	2	16.9	29.4	239	83	190	206	216	220	206
	11	1	20.7	15.1	261	107	231	249	260	263	243
	12		22.0	0.0	267	115	245	264	275	278	255
			Surface Daily Totals		1710	596	1360	1478	1550	1578	1478
Feb 21	7	5	2.4	72.2	12	1	3	4	4	4	4
	8	4	11.6	60.5	188	49	95	102	105	106	96
	9	3	19.7	47.7	251	100	178	187	191	190	167
	10	2	26.2	33.3	278	139	240	251	255	251	217
	11	1	30.5	17.2	290	165	278	290	294	288	247
	12		32.0	0.0	293	173	291	304	307	301	258
			Surface Daily Totals		2330	1080	1880	1972	2024	1978	1720
Mar 21	7	5	10.0	78.7	153	37	49	49	47	45	35
	8	4	19.5	66.8	236	96	131	132	129	122	96
	9	3	28.2	53.4	270	147	205	207	203	193	152
	10	2	35.4	37.8	287	187	263	266	261	248	195
	11	1	40.3	19.8	295	212	300	303	297	283	223
	12		42.0	0.0	298	220	312	315	309	294	232
			Surface Daily Totals		2780	1578	2208	2228	2182	2074	1632
Apr 21	6	6	8.6	97.8	108	27	13	9	8	7	5
	7	5	18.6	86.7	205	85	76	68	59	48	21
	8	4	28.5	74.9	247	142	149	141	129	113	69
	9	3	37.8	61.2	268	191	216	208	194	174	115
	10	2	45.8	44.6	280	228	268	260	245	223	152
	11	1	51.5	24.0	286	252	301	294	278	254	177
	12		53.6	0.0	288	260	313	305	289	264	185
			Surface Daily Totals		3076	2106	2358	2266	2114	1902	1262
May 21	5	7	5.2	114.3	41	9	4	4	4	3	2
	6	6	14.7	103.7	162	61	27	16	15	13	10
	7	5	24.6	93.0	219	118	89	75	60	43	13
	8	4	34.7	81.6	248	171	156	142	123	101	45
	9	3	44.3	68.3	264	217	217	202	182	156	86
	10	2	53.0	51.3	274	252	265	251	229	200	120
	11	1	59.5	28.6	279	274	296	281	258	228	141
	12		62.0	0.0	280	281	306	292	269	238	149
			Surface Daily Totals		3254	2482	2418	2234	2010	1728	982
Jun 21	5	7	7.9	116.5	77	21	9	9	8	7	5
	6	6	17.2	106.2	172	74	33	19	18	16	12
	7	5	27.0	95.8	220	129	93	77	59	39	15
	8	4	37.1	84.6	246	181	157	140	119	95	35
	9	3	46.9	71.6	261	225	216	198	175	147	74
	10	2	55.8	54.8	269	259	262	244	220	189	105
	11	1	62.7	31.2	274	280	291	273	248	216	126
	12		65.5	0.0	275	287	301	283	258	225	133
			Surface Daily Totals		3312	2626	2420	2204	1950	1644	874

TABLE C.13 Solar Position and Clear-Day Insolation, 48° N Latitude (I-P units) (*Continued*)

Date	Solar Time A.M.	Solar Time P.M.	Solar Position Alt	Solar Position Azm	Direct Normal	Global Irradiance (Btu/h ft^2) Horiz	South-Facing Elevation Angle 22	32	42	52	90
Jul 21	5	7	5.7	114.7	43	10	5	5	4	4	3
	6	6	15.2	104.1	156	62	28	18	16	15	11
	7	5	25.1	93.5	211	118	89	75	59	42	14
	8	4	35.1	82.1	240	171	154	140	121	99	43
	9	3	44.8	68.8	256	215	214	199	178	153	83
	10	2	53.5	51.9	266	250	261	246	224	195	116
	11	1	60.1	29.0	271	272	291	276	253	223	137
	12		62.6	0.0	272	279	301	286	263	232	144
			Surface Daily Totals		3158	2474	2386	2200	1974	1694	956
Aug 21	6	6	9.1	98.3	99	28	14	10	9	8	6
	7	5	19.1	87.2	190	85	75	67	58	47	20
	8	4	29.0	75.4	232	141	145	137	125	109	65
	9	3	38.4	61.8	254	189	210	201	187	168	110
	10	2	46.4	45.1	266	225	260	252	237	214	146
	11	1	52.2	24.3	272	248	293	285	268	244	169
	12		54.3	0.0	274	256	304	296	279	255	177
			Surface Daily Totals		2898	2086	2300	2200	2046	1836	1208
Sep 21	7	5	10.0	78.7	131	35	44	44	43	40	31
	8	4	19.5	66.8	215	92	124	124	121	115	90
	9	3	28.2	53.4	251	142	196	197	193	183	143
	10	2	35.4	37.8	269	181	251	254	248	236	185
	11	1	40.3	19.8	278	205	287	289	284	269	212
	12		42.0	0.0	280	213	299	302	296	281	221
			Surface Daily Totals		2568	1522	2102	2118	2070	1966	1546
Oct 21	7	5	2.0	71.9	4	0	1	1	1	1	1
	8	4	11.2	60.2	165	44	86	91	95	95	87
	9	3	19.3	47.4	233	94	167	176	180	178	157
	10	2	25.7	33.1	262	133	228	239	242	239	207
	11	1	30.0	17.1	274	157	266	277	281	276	237
	12		31.5	0.0	278	166	279	291	294	288	247
			Surface Daily Totals		2154	1022	1774	1860	1890	1866	1626
Nov 21	8	4	3.6	54.7	36	5	17	19	21	22	22
	9	3	11.2	42.7	179	46	117	129	137	141	135
	10	2	17.1	29.5	233	83	186	202	212	215	201
	11	1	20.9	15.1	255	107	227	245	255	258	238
	12		22.2	0.0	261	115	241	259	270	272	250
			Surface Daily Totals		1668	596	1336	1448	1518	1544	1442
Dec 21	9	3	8.0	40.9	140	27	87	98	105	110	109
	10	2	13.6	28.2	214	63	164	180	192	197	190
	11	1	17.3	14.4	242	86	207	226	239	244	231
	12		18.6	0.0	250	94	222	241	254	260	244
			Surface Daily Totals		1444	446	1136	1250	1326	1364	1304

Source: Reprinted by permission from Peter J. Lunde, *Solar Thermal Engineering*, © 1980, John Wiley & Sons, New York.

TABLE C.14 Solar Position and Clear-Day Insolation, 64° N Latitude (I-P units)

Date	Solar Time A.M.	Solar Time P.M.	Solar Position Alt	Solar Position Azm	Direct Normal	Global Irradiance (Btu/h ft^2) Horiz	South-Facing Elevation Angle 22	32	42	52	90
Jan 21	10	2	2.8	28.1	22	2	17	19	20	20	20
	11	1	5.2	14.1	81	12	72	77	80	81	81
	12		6.0	0.0	100	16	91	98	102	103	103
			Surface Daily Totals		306	45	268	290	302	306	304
Feb 21	8	4	3.4	58.7	35	4	17	19	19	19	19
	9	3	8.6	44.8	147	31	103	108	111	110	107
	10	2	12.6	30.3	199	55	170	178	181	178	173
	11	1	15.1	15.3	222	71	212	220	223	219	213
	12		16.0	0.0	228	77	225	235	237	232	226
			Surface Daily Totals		1432	400	1230	1286	1302	1282	1252
Mar 21	7	5	6.5	76.5	95	18	30	29	29	27	25
	8	4	12.7	62.6	185	54	101	102	99	94	89
	9	3	18.1	48.1	227	87	171	172	169	160	153
	10	2	22.3	32.7	249	112	227	229	224	213	203
	11	1	25.1	16.6	260	129	262	265	259	246	235
	12		26.0	0.0	263	134	274	277	271	258	246
			Surface Daily Totals		2296	932	1856	1870	1830	1736	1656
Apr 21	5	7	4.0	108.5	27	5	2	2	2	1	1
	6	6	10.4	95.1	133	37	15	9	8	7	6
	7	5	17.0	81.6	194	76	70	63	54	43	37
	8	4	23.3	67.5	228	112	136	128	116	102	91
	9	3	29.0	52.3	248	144	197	189	176	158	145
	10	2	33.5	36.0	260	169	246	239	224	203	188
	11	1	36.5	18.4	266	184	278	270	255	233	216
	12		37.6	0.0	268	190	289	281	266	243	225
			Surface Daily Totals		2982	1644	2176	2082	1936	1736	1594
May 21	4	8	5.8	125.1	51	11	5	4	4	3	3
	5	7	11.6	112.1	132	42	13	11	10	9	8
	6	6	17.9	99.1	185	79	29	16	14	12	11
	7	5	24.5	85.7	218	117	86	72	56	39	28
	8	4	30.9	71.5	239	152	148	133	115	94	80
	9	3	36.8	56.1	252	182	204	190	170	145	128
	10	2	41.6	38.9	261	205	249	235	213	186	167
	11	1	44.9	20.1	265	219	278	264	242	213	193
	12		46.0	0.0	267	224	288	274	251	222	201
			Surface Daily Totals		3470	2236	2312	2124	1898	1624	1436
Jun 21	3	9	4.2	139.4	21	4	2	2	2	2	1
	4	8	9.0	126.4	93	27	10	9	8	7	6
	5	7	14.7	113.6	154	60	16	15	13	11	10
	6	6	21.0	100.8	194	96	34	19	17	14	13
	7	5	27.5	87.5	221	132	91	74	55	36	23
	8	4	34.0	73.3	239	166	150	133	112	88	73
	9	3	39.9	57.8	251	195	204	187	164	137	119
	10	2	44.9	40.4	258	217	247	230	206	177	157
	11	1	48.3	20.9	262	231	275	258	233	202	181
	12		49.5	0.0	263	235	284	267	242	211	189
			Surface Daily Totals		3650	2488	2342	2118	1862	1558	1356

TABLE C.14 Solar Position and Clear-Day Insolation, 64° N Latitude (I-P units) (*Continued*)

	Solar Time		Solar Position				Global Irradiance (Btu/h ft^2)				
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jul 21	4	8	6.4	125.3	53	13	6	5	5	4	4
	5	7	12.1	112.4	128	44	14	13	11	10	9
	6	6	18.4	99.4	179	81	30	17	16	13	12
	7	5	25.0	86.0	211	118	86	72	56	38	28
	8	4	31.4	71.8	231	152	146	131	113	91	77
	9	3	37.3	56.3	245	182	201	186	166	141	124
	10	2	42.2	39.2	253	204	245	230	208	181	162
	11	1	45.4	20.2	257	218	273	258	236	207	187
	12		46.6	0.0	259	223	282	267	245	216	195
			Surface Daily Totals		3372	2248	2280	2090	1864	1588	1400
Aug 21	5	7	4.6	108.8	29	6	3	3	2	2	2
	6	6	11.0	95.5	123	39	16	11	10	8	7
	7	5	17.6	81.9	181	77	69	61	52	42	35
	8	4	23.9	67.8	214	113	131	123	112	97	87
	9	3	29.6	52.6	234	144	190	182	169	150	138
	10	2	34.2	36.2	246	168	237	229	215	194	179
	11	1	37.2	18.5	252	183	268	260	244	222	205
	12		38.3	0.0	254	188	278	270	255	232	215
			Surface Daily Totals		2808	1646	2108	2008	1860	1662	1522
Sep 21	7	5	6.5	76.5	77	16	25	24	24	23	21
	8	4	12.7	62.6	163	51	92	92	90	85	81
	9	3	18.1	48.1	206	83	159	159	156	147	141
	10	2	22.3	32.7	229	108	212	213	209	198	189
	11	1	25.1	16.6	240	124	246	248	243	230	220
	12		26.0	0.0	244	129	258	260	254	241	230
			Surface Daily Totals		2074	892	1726	1736	1696	1608	1532
Oct 21	8	4	3.0	58.5	17	2	9	9	10	10	10
	9	3	8.1	44.6	122	26	86	91	93	92	90
	10	2	12.1	30.2	176	50	152	159	161	159	155
	11	1	14.6	15.2	201	65	193	201	203	200	195
	12		15.5	0.0	208	71	207	215	217	213	208
			Surface Daily Totals		1238	358	1088	1136	1152	1134	1106
Nov 21	10	2	3.0	28.1	23	3	18	20	21	21	21
	11	1	5.4	14.2	79	12	70	76	79	80	79
	12		6.2	0.0	97	17	89	96	100	101	100
			Surface Daily Totals		302	46	266	286	298	302	300
Dec 21	11	1	1.8	13.7	4	0	3	4	4	4	4
	12		2.6	0.0	16	2	14	15	16	17	17
			Surface Daily Totals		24	2	20	22	24	24	24

Source: Reprinted by permission from Peter J. Lunde, *Solar Thermal Engineering*, © 1980, John Wiley & Sons, New York.

TABLE C.15 Solar Position and Clear-Day Insolation for 32° N Latitude (SI units)

	Solar Time		Solar Position			Global Irradiance (W/m^2)					
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jan 21	7	5	1.4	65.2	3	0	0	0	0	3	3
	8	4	12.5	56.5	641	177	293	334	366	388	363
	9	3	22.5	46.0	849	372	552	609	650	669	571
	10	2	30.6	33.1	931	527	741	808	849	865	697
	11	1	36.1	17.5	965	625	861	931	972	984	773
	12		38.0	0.0	978	659	899	972	1013	1022	798
			Surface Daily Totals		7755	4064	5802	6335	6682	6834	5613
Feb 21	7	5	7.1	73.5	382	69	107	117	126	133	120
	8	4	19.0	64.4	779	300	401	429	442	445	341
	9	3	29.9	53.4	909	508	650	685	700	694	499
	10	2	39.1	39.4	965	669	839	877	893	880	609
	11	1	45.6	21.4	994	770	959	1000	1013	994	675
	12		48.0	0.0	1000	805	997	1041	1054	1035	700
			Surface Daily Totals		9061	5439	6903	7257	7399	7326	5187
Mar 21	7	5	12.7	81.9	584	170	189	189	186	177	101
	8	4	25.1	73.0	820	407	461	464	454	432	246
	9	3	36.8	62.1	915	612	700	707	694	659	376
	10	2	47.3	47.5	959	773	883	893	877	836	473
	11	1	55.0	26.8	981	874	1000	1013	994	947	536
	12		58.0	0.0	987	906	1038	1051	1032	985	558
			Surface Daily Totals		9503	6575	7503	7582	7440	7086	4026
Apr 21	6	6	6.1	99.9	208	44	28	19	19	16	10
	7	5	18.8	92.2	650	271	246	224	196	161	32
	8	4	31.5	84.0	805	499	492	467	429	397	110
	9	3	43.9	74.2	877	694	710	685	641	577	215
	10	2	55.7	60.3	915	842	880	858	808	738	300
	11	1	65.4	37.5	931	937	988	965	915	836	353
	12		69.6	0.0	937	968	1025	1003	950	871	372
			Surface Daily Totals		9705	7541	7711	7433	6960	6291	2410
May 21	6	6	10.4	107.2	375	114	66	41	41	38	22
	7	5	22.8	100.1	666	338	278	237	189	139	41
	8	4	35.4	92.9	789	552	502	458	401	331	47
	9	3	48.1	84.7	849	735	704	659	593	514	104
	10	2	60.6	73.3	883	874	861	817	748	656	177
	11	1	72.0	51.9	899	962	962	915	846	748	227
	12		78.0	0.0	902	994	994	950	877	779	243
			Surface Daily Totals		9818	8146	7742	7206	6512	5641	1480
Jun 21	6	6	12.2	110.2	413	142	82	51	47	44	28
	7	5	24.3	103.4	663	363	287	240	186	129	44
	8	4	36.9	96.8	773	568	502	451	385	312	51
	9	3	49.6	89.4	833	745	697	644	571	483	60
	10	2	62.2	79.7	865	880	846	792	716	622	129
	11	1	74.2	60.9	880	965	943	890	811	707	177
	12		81.5	0.0	883	994	975	921	842	738	189
			Surface Daily Totals		9730	8310	7686	7048	6279	5332	1167

TABLE C.15 Solar Position and Clear-Day Insolation for 32° N Latitude (SI units) (*Continued*)

	Solar Time		*Solar Position*				*Global Irradiance (W/m²)*				
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jul 21	6	6	10.7	107.7	357	117	69	44	41	38	25
	7	5	23.1	100.6	640	338	274	237	189	139	44
	8	4	35.7	93.6	760	549	498	451	394	328	50
	9	3	48.4	85.5	823	726	694	647	584	502	98
	10	2	60.9	74.3	855	864	849	801	732	644	170
	11	1	72.4	53.3	874	953	947	899	827	732	218
	12		78.6	0.0	880	981	978	934	861	764	233
			Surface Daily Totals		9503	8070	7641	7099	6405	5534	1445
Aug 21	6	6	6.5	100.5	186	44	28	22	19	19	13
	7	5	19.1	92.8	599	268	243	218	189	158	38
	8	4	31.8	84.7	757	492	480	454	416	366	104
	9	3	44.3	75.0	830	681	694	669	622	562	205
	10	2	56.1	61.3	871	827	858	833	786	713	287
	11	1	66.0	38.4	890	921	962	940	887	811	338
	12		70.3	0.0	896	953	1000	975	921	846	357
			Surface Daily Totals		9156	7421	7534	7244	6764	6102	2322
Sep 21	7	5	12.7	81.9	514	161	177	177	174	164	95
	8	4	25.1	73.0	757	391	442	445	435	413	237
	9	3	36.8	62.1	858	593	672	678	666	634	360
	10	2	47.3	47.5	905	748	852	861	846	805	457
	11	1	55.0	26.8	928	846	965	975	956	912	517
	12		58.0	0.0	934	877	1003	1013	994	947	540
			Surface Daily Totals		8859	6354	7219	7282	7143	6796	3868
Oct 21	7	5	6.8	73.1	312	60	91	101	107	114	101
	8	4	18.7	64.0	722	284	379	404	420	423	328
	9	3	29.5	53.0	861	489	625	565	672	669	483
	10	2	38.7	39.1	924	644	811	849	861	852	593
	11	1	45.1	21.1	953	745	928	969	981	965	659
	12		47.5	0.0	959	779	965	1010	1022	1003	685
			Surface Daily Totals		8506	5218	6626	6966	7105	7042	5010
Nov 21	7	5	1.5	65.4	6	0	0	0	3	3	3
	8	4	12.7	56.6	618	174	287	328	357	375	350
	9	3	22.6	46.1	830	372	546	599	637	656	555
	10	2	30.8	33.2	912	524	735	795	836	852	685
	11	1	36.2	17.6	950	622	852	918	956	969	760
	12		38.2	0.0	959	653	890	959	997	1010	786
			Surface Daily Totals		7591	4038	5729	6247	6575	6720	5496
Dec 21	8	4	10.3	53.8	555	129	243	284	319	341	338
	9	3	19.8	43.6	811	322	508	568	615	644	577
	10	2	27.6	31.2	909	473	697	770	817	842	713
	11	1	32.7	16.4	950	568	814	890	940	962	792
	12		34.6	0.0	959	599	855	931	981	1003	817
			Surface Daily Totals		7408	3584	5376	5957	6360	6581	5660

Source: Peter J. Lunde, *Solar Thermal Engineering*, © 1980, John Wiley & Sons, New York; SI conversion by authors.

TABLE C.16 Solar Position and Clear-Day Insolation for 40° N Latitude (SI units)

	Solar Time		*Solar Position*			*Global Irradiance (W/m²)*					
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jan 21	8	4	8.1	55.3	448	88	205	233	256	268	265
	9	3	16.8	44.0	754	262	489	540	574	590	540
	10	2	23.8	30.9	864	401	688	748	786	801	704
	11	1	28.4	16.0	912	486	811	874	915	924	798
	12		30.0	0.0	928	517	852	918	956	965	830
			Surface Daily Totals		6884	2991	5237	5711	6013	6133	5446
Feb 21	7	5	4.8	72.7	218	32	60	66	73	76	69
	8	4	15.4	62.2	707	230	360	385	398	401	338
	9	3	25.0	50.2	864	416	615	647	659	656	527
	10	2	32.8	35.9	931	562	808	842	855	842	663
	11	1	38.1	18.9	962	650	924	965	978	959	745
	12		40.0	0.0	972	681	965	1006	1019	1000	773
			Surface Daily Totals		8329	4461	6499	6821	6947	6865	5458
Mar 21	7	5	11.4	80.2	540	145	174	174	170	161	110
	8	4	22.5	69.6	789	360	442	445	435	413	281
	9	3	32.8	57.3	890	546	678	685	672	637	435
	10	2	41.6	41.9	937	688	861	871	855	814	555
	11	1	47.7	22.6	962	779	978	988	969	924	631
	12		50.0	0.0	969	811	1016	1029	1010	962	656
			Surface Daily Totals		9200	5843	7282	7351	7206	6859	4682
Apr 21	6	6	7.4	98.9	281	63	35	25	22	22	13
	7	5	18.9	89.5	650	274	243	221	192	158	38
	8	4	30.3	79.3	795	480	483	457	420	369	167
	9	3	41.3	67.2	864	653	697	672	628	565	293
	10	2	51.2	51.4	902	789	868	842	795	722	398
	11	1	58.7	29.2	921	874	972	950	899	820	464
	12		61.6	0.0	924	905	1010	988	934	855	486
			Surface Daily Totals		9755	7174	7610	7320	6840	6171	3224
May 21	5	7	1.9	114.7	3	0	0	0	0	0	0
	6	6	12.7	105.6	454	155	79	47	44	41	28
	7	5	24.0	96.6	681	360	281	240	189	139	41
	8	4	35.4	87.2	789	552	498	454	394	328	79
	9	3	46.8	76.0	842	716	697	650	587	505	189
	10	2	57.5	60.9	874	842	852	805	735	647	281
	11	1	66.2	37.1	893	924	950	905	833	738	341
	12		70.0	0.0	896	950	984	937	864	767	360
			Surface Daily Totals		9970	8052	7705	7143	6436	5553	2284
Jun 21	5	7	4.2	117.3	69	13	9	9	6	6	3
	6	6	14.8	108.4	489	189	95	57	54	50	32
	7	5	26.0	99.7	681	388	290	243	186	126	44
	8	4	37.4	90.7	776	574	502	448	382	306	50
	9	3	48.8	80.2	830	735	691	637	565	467	148
	10	2	59.8	65.8	858	858	839	782	707	609	233
	11	1	69.2	41.9	874	934	934	877	798	697	290
	12		73.5	0.0	880	959	965	912	830	726	309
			Surface Daily Totals		10033	8354	7679	7017	6228	5269	1925

TABLE C.16 Solar Position and Clear-Day Insolation for 40° N Latitude (SI units) (*Continued*)

	Solar Time		*Solar Position*				*Global Irradiance (W/m^2)*				
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jul 21	5	7	2.3	115.2	6	0	0	0	0	0	0
	6	6	13.1	106.1	435	158	82	54	47	44	28
	7	5	24.3	97.2	656	360	281	237	189	139	44
	8	4	35.8	87.8	760	549	495	448	391	322	76
	9	3	47.2	76.7	817	710	688	640	574	495	183
	10	2	57.9	61.7	849	836	839	792	722	631	271
	11	1	66.7	37.9	868	915	934	887	814	719	328
	12		70.6	0.0	871	940	969	921	849	751	350
			Surface Daily Totals		9661	7995	7600	7036	6329	5452	2215
Aug 21	6	6	7.9	99.5	256	66	38	28	25	22	16
	7	5	19.3	90.0	603	274	240	218	189	155	38
	8	4	30.7	79.9	748	473	473	445	407	357	158
	9	3	41.8	67.9	820	647	681	653	609	546	281
	10	2	51.7	52.1	858	776	842	817	770	697	379
	11	1	59.3	29.7	877	861	947	921	871	795	442
	12		62.3	0.0	883	890	981	956	905	827	464
			Surface Daily Totals		9200	7080	7427	7124	6638	5976	3086
Sep 21	7	5	11.4	80.2	470	136	161	161	155	148	101
	8	4	22.5	69.6	726	344	420	423	413	391	265
	9	3	32.8	57.3	830	527	650	656	640	609	416
	10	2	41.6	41.9	883	666	827	836	820	779	530
	11	1	47.7	22.6	905	754	940	950	931	887	606
	12		50.0	0.0	915	786	978	988	969	921	631
			Surface Daily Totals		8544	5641	6973	7029	6884	6543	4467
Oct 21	7	5	4.5	72.3	151	22	44	47	54	54	50
	8	4	15.0	61.9	644	215	334	357	369	372	316
	9	3	24.5	49.8	811	398	548	615	631	625	505
	10	2	32.4	35.6	883	536	773	811	823	811	640
	11	1	37.6	18.7	918	628	893	931	943	928	722
	12		39.5	0.0	928	656	931	972	984	965	751
			Surface Daily Totals		7742	4253	6190	6499	6619	6543	5218
Nov 21	8	4	8.2	55.4	429	88	199	227	246	259	256
	9	3	17.0	44.1	732	259	480	527	562	577	527
	10	2	24.0	31.0	846	398	678	735	773	786	691
	11	1	28.6	16.1	893	483	801	861	899	909	782
	12		30.2	0.0	909	514	842	905	940	950	814
			Surface Daily Totals		6714	2972	5162	5610	5900	6020	5319
Dec 21	8	4	5.5	53.0	281	44	123	142	158	170	177
	9	3	14.0	41.9	685	205	426	480	517	540	514
	10	2	20.7	29.4	823	338	631	697	741	764	697
	11	1	25.0	15.2	883	423	754	827	871	893	795
	12		26.6	0.0	899	451	798	868	915	934	830
			Surface Daily Totals		6241	2467	4669	5155	5490	5666	5193

Source: Peter J. Lunde, *Solar Thermal Engineering*, © 1980, John Wiley & Sons, New York; SI conversions by authors.

TABLE C.17 Solar Position and Clear-Day Insolation for 48° N Latitude (SI units)

	Solar Time		Solar Position				Global Irradiance (W/m^2)				
					Direct		South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Normal	Horiz	22	32	42	52	90
Jan 21	8	4	3.5	54.6	117	13	54	60	66	69	69
	9	3	11.0	42.6	584	145	379	416	442	457	439
	10	2	16.9	29.4	754	262	599	650	681	694	650
	11	1	20.7	15.1	823	338	729	786	820	830	767
	12		22.0	0.0	842	363	773	833	868	877	805
			Surface Daily Totals		5395	1880	4291	4663	4890	4979	4663
Feb 21	7	5	2.4	72.2	38	3	9	13	13	13	13
	8	4	11.6	60.5	593	155	300	322	331	334	303
	9	3	19.7	47.7	792	316	562	590	603	599	527
	10	2	26.2	33.3	877	439	757	792	805	792	685
	11	1	30.5	17.2	915	521	877	915	928	909	779
	12		32.0	0.0	924	546	918	959	969	950	814
			Surface Daily Totals		7351	3407	5931	6222	6386	6241	5427
Mar 21	7	5	10.0	78.7	483	117	155	155	148	142	110
	8	4	19.5	66.8	745	303	413	416	407	385	303
	9	3	28.2	53.4	852	464	647	653	640	609	480
	10	2	35.4	37.8	905	590	830	839	823	782	615
	11	1	40.3	19.8	931	669	947	956	937	893	704
	12		42.0	0.0	940	694	984	994	975	928	732
			Surface Daily Totals		8771	4979	6966	7029	6884	6543	5149
Apr 21	6	6	8.6	97.8	341	85	41	28	25	22	16
	7	5	18.6	86.7	647	268	240	215	186	151	66
	8	4	28.5	74.9	779	448	470	445	407	357	218
	9	3	37.8	61.2	846	603	681	656	612	549	363
	10	2	45.8	44.6	883	719	846	820	773	704	480
	11	1	51.5	24.0	902	795	950	928	877	801	558
	12		53.6	0.0	909	820	988	962	912	833	584
			Surface Daily Totals		9705	6644	7439	7149	6670	6001	3982
May 21	5	7	5.2	114.3	129	28	13	13	13	9	6
	6	6	14.7	103.7	511	192	85	50	47	41	32
	7	5	24.6	93.0	691	372	281	237	189	136	41
	8	4	34.7	81.6	782	540	492	448	388	319	142
	9	3	44.3	68.3	833	685	685	637	574	492	271
	10	2	53.0	51.3	864	795	836	792	722	631	379
	11	1	59.5	28.6	880	864	934	887	814	719	445
	12		62.0	0.0	883	887	965	921	849	751	470
			Surface Daily Totals		10266	7831	7629	7048	6342	5452	3098
Jun 21	5	7	7.9	116.5	243	66	28	28	25	22	16
	6	6	17.2	106.2	543	233	104	60	57	50	38
	7	5	27.0	95.8	694	407	293	243	186	123	47
	8	4	37.1	84.6	776	571	495	442	375	300	110
	9	3	46.9	71.6	823	710	681	625	552	464	233
	10	2	55.8	54.8	849	817	827	770	694	596	331
	11	1	62.7	31.2	864	883	918	861	782	681	398
	12		65.5	0.0	868	905	950	893	814	710	420
			Surface Daily Totals		10449	8285	7635	6954	6152	5187	2757

TABLE C.17 Solar Position and Clear-Day Insolation for 48° N Latitude (SI units) (*Continued*)

	Solar Time		Solar Position			Global Irradiance (W/m²)					
					Direct		South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Normal	Horiz	22	32	42	52	90
Jul 21	5	7	5.7	114.7	136	32	16	16	13	13	9
	6	6	15.2	104.1	492	196	88	57	50	47	35
	7	5	25.1	93.5	666	372	281	237	186	133	44
	8	4	35.1	82.1	757	540	486	442	382	312	136
	9	3	44.8	68.8	808	678	675	628	562	483	262
	10	2	53.5	51.9	839	789	823	776	707	615	366
	11	1	60.1	29.0	855	858	918	871	798	704	432
	12		62.6	0.0	858	880	950	902	830	732	454
			Surface Daily Totals		9963	7805	7528	6941	6228	5345	3016
Aug 21	6	6	9.1	98.3	312	88	44	32	28	25	19
	7	5	19.1	87.2	599	268	237	211	183	148	63
	8	4	29.0	75.4	732	445	457	432	394	344	205
	9	3	38.4	61.8	801	596	663	634	590	530	347
	10	2	46.4	45.1	839	710	820	795	748	675	461
	11	1	52.2	24.3	858	782	924	899	846	770	533
	12		54.3	0.0	864	808	959	934	880	805	558
			Surface Daily Totals		9143	6581	7257	6941	6455	5793	3811
Sep 21	7	5	10.0	78.7	413	110	139	139	136	126	98
	8	4	19.5	66.8	678	290	391	391	382	363	284
	9	3	28.2	53.4	792	448	618	622	609	577	451
	10	2	35.4	37.8	849	571	792	801	782	745	584
	11	1	40.3	19.8	877	647	905	912	896	849	669
	12		42.0	0.0	883	672	943	953	934	887	697
			Surface Daily Totals		8102	4802	6632	6682	6531	6203	4878
Oct 21	7	5	2.0	71.9	13	0	3	3	3	3	3
	8	4	11.2	60.2	521	139	271	287	300	300	274
	9	3	19.3	47.4	735	297	527	555	568	562	495
	10	2	25.7	33.1	827	420	719	754	764	754	653
	11	1	30.0	17.1	864	495	839	874	887	871	748
	12		31.5	0.0	877	524	880	918	928	909	779
			Surface Daily Totals		6796	3224	5597	5868	5963	5887	5130
Nov 21	8	4	3.6	54.7	114	16	54	60	66	69	69
	9	3	11.2	42.7	565	145	369	407	432	445	426
	10	2	17.1	29.5	735	262	587	637	669	678	634
	11	1	20.9	15.1	805	338	716	773	805	814	751
	12		22.2	0.0	823	363	760	817	852	858	789
			Surface Daily Totals		5263	1880	4215	4568	4789	4871	4550
Dec 21	9	3	8.0	40.9	442	85	274	309	331	347	344
	10	2	13.6	28.2	675	199	517	568	606	622	599
	11	1	17.3	14.4	764	271	653	713	754	770	729
	12		18.6	0.0	789	297	700	760	801	820	770
			Surface Daily Totals		4556	1407	3584	3944	4184	4303	4114

Source: Peter J. Lunde, *Solar Thermal Engineering*, © 1980, John Wiley & Sons, New York: SI conversions by authors.

TABLE C.18 Solar Position and Clear-Day Insolation for 64° N Latitude (SI units)

	Solar Time		Solar Position				Global Irradiance (W/m²)				
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jan 21	10	2	2.8	28.1	69	6	54	60	63	63	63
	11	1	5.2	14.1	256	38	227	243	252	256	256
	12		6.0	0.0	316	50	287	309	322	325	325
			Surface Daily Totals		965	142	846	915	953	965	959
Feb 21	8	4	3.4	58.7	110	13	54	60	60	60	60
	9	3	8.6	44.8	464	98	325	341	350	347	338
	10	2	12.6	30.3	628	174	536	562	571	562	546
	11	1	15.1	15.3	700	224	669	694	704	691	672
	12		16.0	0.0	719	243	710	741	748	732	713
			Surface Daily Totals		4518	1262	3881	4057	4108	4045	3950
Mar 21	7	5	6.5	76.5	300	57	95	91	91	85	79
	8	4	12.7	62.6	584	170	319	322	312	297	281
	9	3	18.1	48.1	716	274	540	543	533	505	483
	10	2	22.3	32.7	786	353	716	722	707	672	640
	11	1	25.1	16.6	820	407	827	836	817	776	741
	12		26.0	0.0	830	423	864	874	855	814	776
			Surface Daily Totals		7244	2940	5856	5900	5774	5477	5225
Apr 21	5	7	4.0	108.5	85	16	6	6	6	3	3
	6	6	10.4	95.1	420	117	47	28	25	22	19
	7	5	17.0	81.6	612	240	221	199	170	136	117
	8	4	23.3	67.5	719	353	429	404	366	322	287
	9	3	29.0	52.3	782	454	622	596	555	498	457
	10	2	33.5	36.0	820	533	776	754	707	640	593
	11	1	36.5	18.4	839	581	877	852	805	735	681
	12		37.6	0.0	846	599	912	887	839	767	710
			Surface Daily Totals		9408	5187	6865	6569	6108	5477	5029
May 21	4	8	5.8	125.1	161	35	16	13	13	9	9
	5	7	11.6	112.1	416	133	41	35	32	38	25
	6	6	17.9	99.1	584	249	91	50	44	38	35
	7	5	24.5	85.7	688	369	271	227	177	123	88
	8	4	30.9	71.5	754	480	467	420	363	297	252
	9	3	36.8	56.1	795	574	644	600	536	458	404
	10	2	41.6	38.9	823	647	786	741	672	587	527
	11	1	44.9	20.1	836	691	877	833	764	672	609
	12		46.0	0.0	842	707	909	864	792	700	634
			Surface Daily Totals		10948	7055	7294	6701	5988	5124	4531
Jun 21	3	9	4.2	139.4	66	13	6	6	6	6	3
	4	8	9.0	126.4	293	85	32	28	25	22	19
	5	7	14.7	113.6	486	189	50	47	41	35	32
	6	6	21.0	100.8	612	303	107	60	54	44	41
	7	5	27.5	87.5	697	416	287	233	174	114	73
	8	4	34.0	73.3	754	524	473	420	353	278	230
	9	3	39.9	57.8	792	615	644	590	517	432	375
	10	2	44.9	40.4	814	685	779	726	650	558	495
	11	1	48.3	20.9	827	729	868	814	735	637	571
	12		49.5	0.0	830	741	896	842	764	666	596
			Surface Daily Totals		11516	7850	7389	6682	5875	4915	4278

TABLE C.18 Solar Position and Clear-Day Insolation for 64° N Latitude (SI units) (*Continued*)

	Solar Time		Solar Position				Global Irradiance (W/m²)				
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	22	32	42	52	90
Jul 21	4	8	6.4	125.3	167	41	19	16	16	13	13
	5	7	12.1	112.4	404	139	44	41	35	32	28
	6	6	18.4	99.4	565	256	95	54	50	41	38
	7	5	25.0	86.0	666	372	271	227	177	120	88
	8	4	31.4	71.8	729	480	461	413	357	287	243
	9	3	37.3	56.3	773	574	634	587	524	445	391
	10	2	42.2	39.2	798	644	773	626	656	571	511
	11	1	45.4	20.2	811	688	861	814	745	653	590
	12		46.6	0.0	817	704	890	842	773	681	615
			Surface Daily Totals		10639	7092	7193	6594	5881	5010	4417
Aug 21	5	7	4.6	108.8	91	19	9	9	6	6	6
	6	6	11.0	95.5	388	123	50	35	32	25	22
	7	5	17.6	81.9	571	243	218	192	164	133	110
	8	4	23.9	67.8	675	357	413	388	353	306	274
	9	3	29.6	52.6	738	454	599	574	533	473	435
	10	2	34.2	36.2	776	530	748	722	678	612	565
	11	1	37.2	18.5	795	577	846	820	770	700	647
	12		38.3	0.0	801	593	877	852	805	732	678
			Surface Daily Totals		8859	5193	6651	6335	5868	5244	4802
Sep 21	7	5	6.5	76.5	243	50	79	76	76	73	66
	8	4	12.7	62.6	514	161	290	290	284	268	256
	9	3	18.1	48.1	650	262	502	502	492	464	445
	10	2	22.3	32.7	722	341	669	672	659	625	596
	11	1	25.1	16.6	757	391	776	782	767	726	694
	12		26.0	0.0	770	407	814	820	801	760	726
			Surface Daily Totals		6543	2814	5446	5477	5351	5073	4833
Oct 21	8	4	3.0	58.5	54	6	28	28	32	32	32
	9	3	8.1	44.6	385	82	271	287	293	290	284
	10	2	12.1	30.2	555	158	480	502	508	502	489
	11	1	14.6	15.2	634	205	609	634	640	631	615
	12		15.5	0.0	656	224	653	678	685	672	656
			Surface Daily Totals		3906	1129	3433	3584	3635	3578	3489
Nov 21	10	2	3.0	28.1	73	9	57	63	66	66	66
	11	1	5.4	14.2	249	38	221	240	249	252	249
	12		6.2	0.0	306	54	281	303	316	319	316
			Surface Daily Totals		953	145	839	902	940	953	947
Dec 21	11	1	1.8	13.7	13	0	9	13	13	13	13
	12		2.6	0.0	50	6	44	47	50	54	54
			Surface Daily Totals		76	6	62	73	76	80	80

Source: Peter J. Lunde, *Solar Thermal Engineering*, © 1980, John Wiley & Sons, New York: SI conversions by authors.

Fig. C.1 *U.S. and Canadian locations for which solar data are given in Tables C.19 and C.20. Basic temperature data for many more locations are found in Appendix B. (Adapted by permission from J.D. Balcomb et al.,* Passive Solar Design Handbook, *Vol. 3, © 1983, American Solar Energy Society, Inc., Boulder, CO.)*

TABLE C.19 Average Insolation, Temperature, and DD Data (I-P units)

Elevation in feet; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in Btu/day ft^2; TA in degrees F; D50, D55, D60, and D65 in degree days F (for these various "base" temperatures).

United States

MONTGOMERY, ALABAMA Elev 203 Lat 32.3

	HS	VS	TA	D50	D55	D60	D65
Jan	752	896	48	148	256	394	556
Jul	1841	820	81	0	0	0	0
Yr	1390	946	65	445	866	1474	2269

PHOENIX, ARIZONA Elev 1112 Lat 33.4

	HS	VS	TA	D50	D55	D60	D65
Jan	1021	1462	51	78	162	285	428
Jul	2486	964	91	0	0	0	0
Yr	1371	1326	70	187	459	919	1552

TUCSON, ARIZONA Elev 2556 Lat 32.1

	HS	VS	TA	D50	D55	D60	D65
Jan	1099	1539	51	80	166	292	442
Jul	2341	922	86	0	0	0	0
Yr	1874	1307	68	214	525	1036	1752

FORT SMITH, ARKANSAS Elev 463 Lat 35.3

	HS	VS	TA	D50	D55	D60	D65
Jan	744	996	39	346	497	651	806
Jul	2065	908	82	0	0	0	0
Yr	1406	1013	61	996	1622	2405	3336

FRESNO, CALIFORNIA Elev 328 Lat 36.8

	HS	VS	TA	D50	D55	D60	D65
Jan	657	886	45	176	308	457	611
Jul	2685	1076	81	0	0	0	0
Yr	1714	1210	62	507	1021	1741	2650

LOS ANGELES, CALIFORNIA Elev 105 Lat 33.9

	HS	VS	TA	D50	D55	D60	D65
Jan	926	1293	55	21	83	186	331
Jul	2307	942	69	0	1	5	19
Yr	1596	1157	62	64	299	849	1819

SACRAMENTO, CALIFORNIA Elev 26 Lat 38.5

	HS	VS	TA	D50	D55	D60	D65
Jan	597	829	45	183	315	464	617
Jul	2688	1131	75	0	0	0	0
Yr	1646	1198	60	554	1097	1871	2843

SAN DIEGO, CALIFORNIA Elev 30 Lat 32.7

	HS	VS	TA	D50	D55	D60	D65
Jan	976	1325	55	9	58	160	314
Jul	2186	902	70	0	0	1	6
Yr	1600	1151	63	23	170	623	1507

SAN FRANCISCO, CALIFORNIA Elev 16 Lat 37.6

	HS	VS	TA	D50	D55	D60	D65
Jan	708	1023	48	82	210	363	518
Jul	2392	1034	63	0	2	21	93
Yr	1556	1156	57	202	705	1643	3042

SANTA MARIA, CALIFORNIA Elev 236 Lat 34.9

	HS	VS	TA	D50	D55	D60	D65
Jan	854	1198	51	51	150	296	450
Jul	2341	965	62	0	3	30	112
Yr	1610	1172	57	155	624	1604	3053

DENVER, COLORADO Elev 5331 Lat 39.7

	HS	VS	TA	D50	D55	D60	D65
Jan	840	1465	30	623	778	933	1088
Jul	2273	1053	73	0	0	0	0
Yr	1570	1334	50	2592	3588	4733	6016

GRAND JUNCTION, COLORADO Elev 4839 Lat 39.1

	HS	VS	TA	D50	D55	D60	D65
Jan	791	1296	27	726	880	1035	1190
Jul	2465	1094	79	0	0	0	0
Yr	1661	1346	53	2514	3412	4434	5605

HARTFORD, CONNECTICUT Elev 180 Lat 41.9

	HS	VS	TA	D50	D55	D60	D65
Jan	477	694	25	781	936	1091	1246
Jul	1649	861	73	0	0	0	0
Yr	1060	835	49	2971	3948	5075	6350

WASHINGTON, DC Elev 289 Lat 38.9

	HS	VS	TA	D50	D55	D60	D65
Jan	572	793	32	555	710	865	1020
Jul	1817	883	75	0	0	0	0
Yr	1210	912	54	2004	2869	3864	5010

MIAMI, FLORIDA Elev 7 Lat 25.8

	HS	VS	TA	D50	D55	D60	D65
Jan	1057	1121	67	1	4	18	53
Jul	1763	787	82	0	0	0	0
Yr	1474	941	76	3	14	55	206

ORLANDO, FLORIDA Elev 118 Lat 28.5

	HS	VS	TA	D50	D55	D60	D65
Jan	999	1151	60	13	42	105	197
Jul	1801	795	81	0	0	0	0
Yr	1488	984	72	39	126	348	733

TALLAHASSEE, FLORIDA Elev 69 Lat 30.4

	HS	VS	TA	D50	D55	D60	D65
Jan	877	1033	53	73	150	256	408
Jul	1748	786	81	0	0	0	0
Yr	1434	969	68	215	501	951	1563

ATLANTA, GEORGIA Elev 1033 Lat 33.6

	HS	VS	TA	D50	D55	D60	D65
Jan	718	884	42	246	393	546	701
Jul	1812	821	78	0	0	0	0
Yr	1347	941	61	758	1362	2150	3095

BOISE, IDAHO Elev 2867 Lat 43.6

	HS	VS	TA	D50	D55	D60	D65
Jan	485	770	29	651	806	961	1116
Jul	2613	1309	75	0	0	0	0
Yr	1499	1255	51	2420	3395	4536	5833

CHICAGO, ILLINOIS Elev 623 Lat 41.8

	HS	VS	TA	D50	D55	D60	D65
Jan	507	756	24	797	952	1107	1262
Jul	1944	984	75	0	0	0	0
Yr	1217	960	51	2954	3881	4940	6127

MOLINE, ILLINOIS Elev 594 Lat 41.4

	HS	VS	TA	D50	D55	D60	D65
Jan	535	803	22	884	1039	1194	1349
Jul	1939	974	75	0	0	0	0
Yr	1226	973	50	3191	4117	5178	6395

SPRINGFIELD, ILLINOIS Elev 614 Lat 39.8

	HS	VS	TA	D50	D55	D60	D65
Jan	585	852	27	723	877	1032	1187
Jul	2058	984	76	0	0	0	0
Yr	1304	1003	53	2558	3434	4425	5558

TABLE C.19 Average Insolation, Temperature, and DD Data (I-P units) (*Continued*)

Elevation in feet; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in Btu/day ft^2; TA in degrees F; D50, D55, D60, and D65 in degree days F (for these various "base" temperatures).

United States

INDIANAPOLIS, INDIANA Elev 807 Lat 39.7

	HS	VS	TA	D50	D55	D60	D65
Jan	496	668	28	685	840	995	1150
Jul	1806	891	75	0	0	0	0
Yr	1167	873	52	2511	3403	4421	5577

SOUTH BEND, INDIANA Elev 774 Lat 41.7

	HS	VS	TA	D50	D55	D60	D65
Jan	416	566	24	806	961	1116	1271
Jul	1852	944	72	0	1	4	6
Yr	1140	864	49	3112	4084	5199	6462

DES MOINES, IOWA Elev 965 Lat 41.5

	HS	VS	TA	D50	D55	D60	D65
Jan	581	912	19	949	1104	1259	1414
Jul	2097	1037	75	0	0	0	0
Yr	1314	1065	49	3491	4435	5510	6710

DODGE CITY, KANSAS Elev 2582 Lat 37.8

	HS	VS	TA	D50	D55	D60	D65
Jan	827	1303	31	596	750	905	1060
Jul	2295	1013	79	0	0	0	0
Yr	1562	1232	55	2131	2980	3945	5046

TOPEKA, KANSAS Elev 886 Lat 39.1

	HS	VS	TA	D50	D55	D60	D65
Jan	681	1033	28	683	837	992	1147
Jul	2128	993	78	0	0	0	0
Yr	1387	1036	54	2325	3175	4137	5243

LEXINGTON, KENTUCKY Elev 988 Lat 38.0

	HS	VS	TA	D50	D55	D60	D65
Jan	546	714	33	531	685	840	995
Jul	1850	881	76	0	0	0	0
Yr	1221	892	55	1865	2686	3632	4729

BATON ROUGE, LOUISIANA Elev 75 Lat 30.5

	HS	VS	TA	D50	D55	D60	D65
Jan	785	889	51	90	174	294	451
Jul	1746	786	82	0	0	0	0
Yr	1380	913	67	232	530	1006	1670

NEW ORLEANS, LOUISIANA Elev 10 Lat 30.0

	HS	VS	TA	D50	D55	D60	D65
Jan	835	950	53	73	150	252	403
Jul	1813	801	82	0	0	0	0
Yr	1438	943	68	197	465	887	1465

SHREVEPORT, LOUISIANA Elev 259 Lat 32.5

	HS	VS	TA	D50	D55	D60	D65
Jan	762	920	47	154	264	403	552
Jul	2014	864	83	0	0	0	0
Yr	1428	973	66	428	832	1415	2167

PORTLAND, MAINE Elev 62 Lat 43.6

	HS	VS	TA	D50	D55	D60	D65
Jan	450	689	22	884	1039	1194	1349
Jul	1659	894	68	0	1	5	27
Yr	1052	857	45	3648	4758	6039	7498

DETROIT, MICHIGAN Elev 627 Lat 42.4

	HS	VS	TA	D50	D55	D60	D65
Jan	417	585	26	760	915	1070	1225
Jul	1835	951	73	0	0	0	0
Yr	1122	869	50	2931	3890	4986	6228

SAULT STE. MARIE, MICHIGAN Elev 725 Lat 46.5

	HS	VS	TA	D50	D55	D60	D65
Jan	325	492	14	1110	1265	1420	1575
Jul	1835	1045	64	1	7	33	96
Yr	1044	861	40	4969	6198	7607	9193

MINNEAPOLIS, MINNESOTA Elev 837 Lat 44.9

	HS	VS	TA	D50	D55	D60	D65
Jan	464	768	12	1172	1327	1482	1637
Jul	1970	1071	72	0	1	5	11
Yr	1172	996	44	4584	5631	6824	8159

MERIDIAN, MISSISSIPPI Elev 308 Lat 32.3

	HS	VS	TA	D50	D55	D60	D65
Jan	744	883	47	163	274	413	575
Jul	1823	815	81	0	0	0	0
Yr	1371	933	65	510	955	1582	2388

SAINT LOUIS, MISSOURI Elev 564 Lat 38.7

	HS	VS	TA	D50	D55	D60	D65
Jan	627	898	31	581	735	890	1045
Jul	2049	959	79	0	0	0	0
Yr	1329	1006	56	1961	2762	3686	4750

SPRINGFIELD, MISSOURI Elev 1270 Lat 37.2

	HS	VS	TA	D50	D55	D60	D65
Jan	684	956	33	534	686	840	995
Jul	2063	936	78	0	0	0	0
Yr	1364	1011	56	1848	2618	3522	4571

HELENA, MONTANA Elev 3898 Lat 46.6

	HS	VS	TA	D50	D55	D60	D65
Jan	419	719	18	989	1144	1299	1454
Jul	2334	1312	68	1	3	12	33
Yr	1266	1134	43	4151	5342	6689	8190

NORTH OMAHA, NEBRASKA Elev 1325 Lat 41.4

	HS	VS	TA	D50	D55	D60	D65
Jan	634	1034	20	924	1079	1234	1389
Jul	2106	1038	75	0	1	3	7
Yr	1323	1078	49	3369	4309	5381	6601

ELY, NEVADA Elev 6253 Lat 39.3

	HS	VS	TA	D50	D55	D60	D65
Jan	819	1380	24	818	973	1128	1283
Jul	2447	1094	67	0	2	11	23
Yr	1675	1391	44	3716	4922	6291	7814

LAS VEGAS, NEVADA Elev 2178 Lat 36.1

	HS	VS	TA	D50	D55	D60	D65
Jan	978	1553	44	216	346	493	645
Jul	2588	1039	90	0	0	0	0
Yr	1866	1431	66	631	1129	1788	2601

RENO, NEVADA Elev 4400 Lat 39.5

	HS	VS	TA	D50	D55	D60	D65
Jan	800	1345	32	561	716	871	1026
Jul	2692	1167	69	0	1	5	17
Yr	1764	1439	49	2292	3345	4590	6022

ALBUQUERQUE, NEW MEXICO Elev 5312 Lat 35.0

	HS	VS	TA	D50	D55	D60	D65
Jan	1016	1562	35	459	614	769	924
Jul	2489	995	79	0	0	0	0
Yr	1830	1379	57	1497	2292	3216	4292

TABLE C.19 Average Insolation, Temperature, and DD Data (I-P units) (*Continued*)

Elevation in feet; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in Btu/day ft^2; TA in degrees F; D50, D55, D60, and D65 in degree days F (for these various "base" temperatures).

United States

LOS ALAMOS, NEW MEXICO — Elev 7380 — Lat 35.9

	HS	VS	TA	D50	D55	D60	D65
Jan	893	1340	29	650	804	958	1113
Jul	2051	913	68	0	0	0	0
Yr	1579	1244	48	2822	3851	5043	6437

BUFFALO, NEW YORK — Elev 705 — Lat 42.9

	HS	VS	TA	D50	D55	D60	D65
Jan	349	465	24	815	970	1125	1280
Jul	1776	935	70	0	0	3	12
Yr	1037	780	47	3322	4363	5551	6927

NEW YORK, NEW YORK — Elev 187 — Lat 40.8

	HS	VS	TA	D50	D55	D60	D65
Jan	500	708	32	552	707	862	1017
Jul	1688	861	77	0	0	0	0
Yr	1101	849	55	1931	2759	3737	4848

SYRACUSE, NEW YORK — Elev 407 — Lat 43.1

	HS	VS	TA	D50	D55	D60	D65
Jan	385	538	24	818	973	1128	1283
Jul	1758	931	72	0	1	3	11
Yr	1037	791	48	3215	4218	5366	6678

ALBANY, NEW YORK — Elev 292 — Lat 42.7

	HS	VS	TA	D50	D55	D60	D65
Jan	456	674	22	884	1039	1194	1349
Jul	1725	908	72	0	1	3	9
Yr	1068	843	48	3424	4428	5586	6888

CHARLOTTE, NORTH CAROLINA — Elev 768 — Lat 35.2

	HS	VS	TA	D50	D55	D60	D65
Jan	719	944	42	255	402	555	710
Jul	1831	841	79	0	0	0	0
Yr	1346	981	61	828	1451	2257	3218

RALEIGH-DURHAM, NORTH CAROLINA — Elev 440 — Lat 35.9

	HS	VS	TA	D50	D55	D60	D65
Jan	694	924	41	300	451	605	760
Jul	1776	832	78	0	0	0	0
Yr	1297	955	59	990	1659	2509	3514

BISMARCK, NORTH DAKOTA — Elev 1647 — Lat 46.8

	HS	VS	TA	D50	D55	D60	D65
Jan	467	847	8	1296	1451	1606	1761
Jul	2184	1241	71	0	2	8	18
Yr	1251	1145	41	5235	6364	7627	9044

FARGO, NORTH DAKOTA — Elev 899 — Lat 46.9

	HS	VS	TA	D50	D55	D60	D65
Jan	415	720	6	1367	1522	1677	1832
Jul	2120	1210	71	0	1	5	13
Yr	1206	1075	41	5485	6607	7858	9271

CINCINNATI, OHIO — Elev 889 — Lat 39.1

	HS	VS	TA	D50	D55	D60	D65
Jan	500	659	31	587	741	896	1051
Jul	1771	869	76	0	0	0	0
Yr	1160	858	54	2117	2973	3951	5070

CLEVELAND, OHIO — Elev 804 — Lat 41.4

	HS	VS	TA	D50	D55	D60	D65
Jan	388	507	27	716	871	1026	1181
Jul	1828	929	71	0	1	4	9
Yr	1093	808	50	2804	3768	4879	6154

COLUMBUS, OHIO — Elev 833 — Lat 40.0

	HS	VS	TA	D50	D55	D60	D65
Jan	459	606	28	670	825	980	1135
Jul	1755	876	74	0	0	0	0
Yr	1128	834	52	2524	3438	4491	5702

OKLAHOMA CITY, OKLAHOMA — Elev 1302 — Lat 35.4

	HS	VS	TA	D50	D55	D60	D65
Jan	801	1114	37	413	565	719	874
Jul	2128	925	82	0	0	0	0
Yr	1463	1073	60	1232	1903	2734	3695

MEDFORD, OREGON — Elev 1299 — Lat 42.4

	HS	VS	TA	D50	D55	D60	D65
Jan	407	565	37	417	571	725	880
Jul	2475	1207	72	0	1	3	11
Yr	1356	1033	53	1576	2505	3621	4930

SALEM, OREGON — Elev 200 — Lat 44.9

	HS	VS	TA	D50	D55	D60	D65
Jan	332	471	39	348	502	657	812
Jul	2142	1154	67	0	1	7	43
Yr	1130	897	52	1265	2220	3411	4852

HARRISBURG, PENNSYLVANIA — Elev 348 — Lat 40.2

	HS	VS	TA	D50	D55	D60	D65
Jan	536	763	30	617	772	927	1082
Jul	1764	883	76	0	0	0	0
Yr	1152	887	53	2221	3093	4086	5224

PHILADELPHIA, PENNSYLVANIA — Elev 30 — Lat 39.9

	HS	VS	TA	D50	D55	D60	D65
Jan	555	792	32	549	704	859	1014
Jul	1758	876	77	0	0	0	0
Yr	1170	905	55	1935	2775	3749	4865

PITTSBURGH, PENNSYLVANIA — Elev 1224 — Lat 40.5

	HS	VS	TA	D50	D55	D60	D65
Jan	424	553	28	679	834	989	1144
Jul	1689	857	72	0	1	3	7
Yr	1071	793	50	2635	3574	4669	5930

PROVIDENCE, RHODE ISLAND — Elev 62 — Lat 41.7

	HS	VS	TA	D50	D55	D60	D65
Jan	506	750	28	670	825	980	1135
Jul	1695	878	72	0	0	0	0
Yr	1114	884	50	2566	3543	4669	5972

CHARLESTON, SOUTH CAROLINA — Elev 39 — Lat 32.9

	HS	VS	TA	D50	D55	D60	D65
Jan	744	904	49	120	222	360	521
Jul	1799	813	80	0	0	0	0
Yr	1346	940	65	360	756	1355	2146

RAPID CITY, SOUTH DAKOTA — Elev 3169 — Lat 44.0

	HS	VS	TA	D50	D55	D60	D65
Jan	542	928	22	871	1026	1181	1336
Jul	2223	1161	73	1	2	8	13
Yr	1344	1177	47	3681	4749	5965	7324

KNOXVILLE, TENNESSEE — Elev 981 — Lat 35.8

	HS	VS	TA	D50	D55	D60	D65
Jan	621	785	41	302	449	602	756
Jul	1804	839	78	0	0	0	0
Yr	1275	909	60	1018	1671	2504	3478

TABLE C.19 Average Insolation, Temperature, and DD Data (I-P units) (*Continued*)

Elevation in feet; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in Btu/day ft^2; TA in degrees F; D50, D55, D60, and D65 in degree days F (for these various "base" temperatures).

United States

MEMPHIS, TENNESSEE Elev 285 Lat 35.0

	HS	VS	TA	D50	D55	D60	D65
Jan	683	870	41	312	455	606	760
Jul	1972	879	82	0	0	0	0
Yr	1368	965	62	988	1588	2357	3227

NASHVILLE, TENNESSEE Elev 591 Lat 36.1

	HS	VS	TA	D50	D55	D60	D65
Jan	580	721	38	369	519	673	828
Jul	1891	869	80	0	0	0	0
Yr	1272	891	59	1195	1874	2720	3696

AUSTIN, TEXAS Elev 620 Lat 30.3

	HS	VS	TA	D50	D55	D60	D65
Jan	864	1008	50	116	207	333	483
Jul	2105	865	85	0	0	0	0
Yr	1478	974	68	289	602	1088	1737

BROWNSVILLE, TEXAS Elev 20 Lat 25.9

	HS	VS	TA	D50	D55	D60	D65
Jan	913	923	60	18	51	116	225
Jul	2212	867	84	0	0	0	0
Yr	1550	917	74	44	127	325	650

DALLAS, TEXAS Elev 489 Lat 32.8

	HS	VS	TA	D50	D55	D60	D65
Jan	821	1035	45	189	312	457	608
Jul	2122	890	86	0	0	0	0
Yr	1470	1014	66	505	943	1543	2290

EL PASO, TEXAS Elev 3917 Lat 31.8

	HS	VS	TA	D50	D55	D60	D65
Jan	1125	1572	44	210	355	509	663
Jul	2450	934	82	0	0	0	0
Yr	1901	1327	63	561	1102	1810	2678

HOUSTON, TEXAS Elev 108 Lat 30.0

	HS	VS	TA	D50	D55	D60	D65
Jan	772	852	52	71	150	263	416
Jul	1828	805	83	0	0	0	0
Yr	1353	884	69	161	409	825	1434

LUBBOCK, TEXAS Elev 3241 Lat 33.6

	HS	VS	TA	D50	D55	D60	D65
Jan	1031	1497	39	343	494	648	803
Jul	2412	956	80	0	0	0	0
Yr	1768	1279	60	1069	1739	2582	3545

SAN ANTONIO, TEXAS Elev 794 Lat 29.5

	HS	VS	TA	D50	D55	D60	D65
Jan	895	1026	51	93	179	302	451
Jul	2121	863	85	0	0	0	0
Yr	1501	973	69	213	490	941	1570

BRYCE CANYON, UTAH Elev 7588 Lat 37.7

	HS	VS	TA	D50	D55	D60	D65
Jan	914	1511	20	936	1091	1246	1401
Jul	2424	1044	62	1	8	47	128
Yr	1742	1404	40	4693	6106	7675	9133

SALT LAKE CITY, UTAH Elev 4226 Lat 40.8

	HS	VS	TA	D50	D55	D60	D65
Jan	639	1017	28	683	837	992	1147
Jul	2590	1186	77	0	0	0	0
Yr	1606	1301	51	2648	3612	4725	5983

BURLINGTON, VERMONT Elev 341 Lat 44.5

	HS	VS	TA	D50	D55	D60	D65
Jan	385	572	17	1029	1184	1339	1494
Jul	1721	941	70	0	1	4	20
Yr	1023	815	44	4142	5230	6464	7876

NORFOLK, VIRGINIA Elev 30 Lat 36.9

	HS	VS	TA	D50	D55	D60	D65
Jan	678	932	41	300	450	605	760
Jul	1853	868	78	0	0	0	0
Yr	1327	990	59	974	1646	2489	3488

RICHMOND, VIRGINIA Elev 164 Lat 37.5

	HS	VS	TA	D50	D55	D60	D65
Jan	632	863	38	390	543	698	853
Jul	1774	849	78	0	0	0	0
Yr	1250	936	58	1296	2021	2909	3939

ROANOKE, VIRGINIA Elev 1175 Lat 37.3

	HS	VS	TA	D50	D55	D60	D65
Jan	660	911	36	423	577	832	887
Jul	1796	854	75	0	0	0	0
Yr	1271	958	56	1486	2277	3211	4307

SEATTLE-TACOMA, WASHINGTON Elev 400 Lat 47.4

	HS	VS	TA	D50	D55	D60	D65
Jan	262	378	38	367	521	676	831
Jul	2248	1299	65	0	2	16	80
Yr	1056	857	51	1386	2393	3662	5185

SPOKANE, WASHINGTON Elev 2365 Lat 47.6

	HS	VS	TA	D50	D55	D60	D65
Jan	315	496	25	763	918	1073	1228
Jul	2357	1368	70	0	2	7	21
Yr	1227	1068	47	3061	4150	5411	6835

CHARLESTON, WEST VIRGINIA Elev 951 Lat 38.4

	HS	VS	TA	D50	D55	D60	D65
Jan	498	638	35	483	636	791	946
Jul	1682	827	75	0	0	0	0
Yr	1125	822	55	1726	2540	3488	4590

MADISON, WISCONSIN Elev 860 Lat 43.1

	HS	VS	TA	D50	D55	D60	D65
Jan	515	822	17	1029	1184	1339	1494
Jul	1934	1009	70	0	1	5	14
Yr	1193	978	45	4086	5143	6352	7730

MILWAUKEE, WISCONSIN Elev 692 Lat 42.9

	HS	VS	TA	D50	D55	D60	D65
Jan	479	731	19	949	1104	1259	1414
Jul	1962	1017	70	0	1	4	15
Yr	1194	957	46	3774	4833	6045	7444

SHERIDAN, WYOMING Elev 3966 Lat 44.8

	HS	VS	TA	D50	D55	D60	D65
Jan	517	900	21	899	1054	1209	1364
Jul	2329	1237	70	1	2	9	28
Yr	1333	1170	45	3860	4991	6279	7708

TABLE C.19 Average Insolation, Temperature, and DD Data (I-P units) (*Continued*)

Elevation in feet; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in Btu/day ft^2; TA in degrees F; D50, D55, D60, and D65 in degree days F (for these various "base" temperatures).

Canada

EDMONTON, ALBERTA — Elev 2220 — Lat 53.6

	HS	VS	TA	D50	D55	D60	D65
Jan	324	746	4	1421	1574	1728	1883
Jul	1977	1378	62	1	7	38	117
Yr	1114	1205	36	6317	7563	9016	10650

SUFFIELD, ALBERTA — Elev 2549 — Lat 50.3

	HS	VS	TA	D50	D55	D60	D65
Jan	433	937	7	1333	1486	1640	1794
Jul	2173	1377	67	0	2	11	49
Yr	1239	1269	40	5500	6637	7923	9393

VANCOUVER, BRITISH COLUMBIA — Elev 310 — Lat 37.5

	HS	VS	TA	D50	D55	D60	D65
Jan	254	395	37	425	572	724	878
Jul	2021	1239	63	0	1	13	82
Yr	1060	916	50	1791	2781	4041	5588

WINNIPEG, MANITOBA — Elev 820 — Lat 49.95

	HS	VS	TA	D50	D55	D60	D65
Jan	461	1011	0	1588	1740	1893	2047
Jul	2025	1264	67	0	2	9	45
Yr	1190	1199	36	6925	8062	9338	10790

HALIFAX, NOVA SCOTIA — Elev 136 — Lat 44.6

	HS	VS	TA	D50	D55	D60	D65
Jan	456	737	26	752	900	1051	1204
Jul	1694	929	65	0	1	8	57
Yr	1076	907	46	3457	4500	5746	7211

OTTAWA, ONTARIO — Elev 377 — Lat 45.5

	HS	VS	TA	D50	D55	D60	D65
Jan	510	914	13	1169	1320	1473	1627
Jul	1875	1040	69	0	1	4	23
Yr	1158	1015	43	4912	5965	7158	8529

TORONTO, ONTARIO — Elev 443 — Lat 43.7

	HS	VS	TA	D50	D55	D60	D65
Jan	487	777	22	891	1041	1194	1348
Jul	1958	1035	70	0	0	3	18
Yr	1171	948	46	3842	4853	6013	7343

NORMANDIN, QUEBEC — Elev 450 — Lat 48.8

	HS	VS	TA	D50	D55	D60	D65
Jan	454	921	0	1564	1719	1873	2028
Jul	1707	1031	62	1	7	40	118
Yr	1092	1053	34	7037	8308	9762	11376

Source: Reprinted by permission from J. D. Balcomb et al., *Passive Solar Design Handbook*, Vol. 3, © 1983, American Solar Energy Society, Inc., Boulder, CO.

TABLE C.20 Average Insolation, Temperature, and DD Data (SI units)

Elevation in meters; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in W/day m^2; TA in degrees C; D10.0, D12.8, D15.6, and D18.3 in degree days C (for these various "base" temperatures).

United States

MONTGOMERY, ALABAMA Elev 62 Lat 32.3

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2373	2827	9	82	142	219	309
Jul	5808	2587	27	0	0	0	0
Yr	4385	2985	18	247	481	819	1261

PHOENIX, ARIZONA Elev 339 Lat 33.4

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3221	4613	11	43	90	158	238
Jul	7843	3041	33	0	0	0	0
Yr	4326	4184	21	104	255	511	862

TUCSON, ARIZONA Elev 779 Lat 32.1

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3467	4856	11	44	92	162	246
Jul	7386	2909	30	0	0	0	0
Yr	5912	4124	20	119	292	576	973

FORT SMITH, ARKANSAS Elev 141 Lat 35.3

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2347	3142	4	192	276	362	448
Jul	6515	2865	28	0	0	0	0
Yr	4436	3196	16	553	901	1336	1853

FRESNO, CALIFORNIA Elev 100 Lat 36.8

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2073	2795	7	98	171	254	339
Jul	8471	3395	27	0	0	0	0
Yr	5408	3818	17	282	567	967	1472

LOS ANGELES, CALIFORNIA Elev 32 Lat 33.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2922	4079	13	12	46	103	184
Jul	7279	2972	21	0	1	3	11
Yr	5035	3650	17	36	166	472	1011

SACRAMENTO, CALIFORNIA Elev 8 Lat 38.5

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1884	2615	7	102	175	258	343
Jul	8481	3568	24	0	0	0	0
Yr	5193	3780	16	308	609	1039	1579

SAN DIEGO, CALIFORNIA Elev 9 Lat 32.7

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3079	4180	13	5	32	89	174
Jul	6897	2846	21	0	0	1	3
Yr	5048	3631	17	13	94	346	837

SAN FRANCISCO, CALIFORNIA Elev 5 Lat 37.6

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2234	3228	9	46	117	202	288
Jul	7547	3262	17	0	1	12	52
Yr	4909	3647	14	112	392	913	1690

SANTA MARIA, CALIFORNIA Elev 72 Lat 34.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2694	3780	11	28	83	164	250
Jul	7386	3045	17	0	2	17	62
Yr	5080	3698	14	86	347	891	1696

DENVER, COLORADO Elev 1625 Lat 39.7

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2650	4622	–1	346	432	518	604
Jul	7171	3322	23	0	0	0	0
Yr	4953	4209	10	1440	1993	2629	3342

GRAND JUNCTION, COLORADO Elev 1475 Lat 39.1

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2496	4089	–3	403	489	575	661
Jul	7777	3452	26	0	0	0	0
Yr	5240	4247	12	1397	1896	2463	3114

HARTFORD, CONNECTICUT Elev 55 Lat 41.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1505	2190	–4	434	520	606	692
Jul	5203	2716	23	0	0	1	3
Yr	3344	2634	9	1651	2193	2819	3528

WASHINGTON, DC Elev 88 Lat 38.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1805	2502	0	308	394	481	567
Jul	5733	2786	24	0	0	0	0
Yr	3818	2877	12	1113	1594	2147	2783

MIAMI, FLORIDA Elev 2 Lat 25.8

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3335	3537	19	1	2	10	29
Jul	5562	2483	28	0	0	0	0
Yr	4650	2969	24	2	8	31	114

ORLANDO, FLORIDA Elev 36 Lat 28.5

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3152	3631	16	7	23	58	109
Jul	5682	2508	27	0	0	0	0
Yr	4695	3105	22	22	70	193	407

TALLAHASSEE, FLORIDA Elev 21 Lat 30.4

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2767	3259	12	41	83	142	227
Jul	5515	2480	27	0	0	0	0
Yr	4524	3057	20	119	278	528	868

ATLANTA, GEORGIA Elev 315 Lat 33.6

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2265	2789	6	137	218	303	389
Jul	5717	2590	26	0	0	0	0
Yr	4250	2969	16	421	757	1194	1719

BOISE, IDAHO Elev 874 Lat 43.6

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1530	2429	–2	362	448	534	620
Jul	8244	4130	24	0	0	0	0
Yr	4729	3960	11	1344	1886	2520	3241

CHICAGO, ILLINOIS Elev 190 Lat 41.8

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1600	2385	–4	443	529	615	701
Jul	6133	3105	24	0	0	0	0
Yr	3840	3029	11	1641	2156	2744	3404

MOLINE, ILLINOIS Elev 181 Lat 41.4

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1688	2533	–6	491	577	663	749
Jul	6118	3073	24	0	0	0	0
Yr	3868	3070	10	1773	2287	2877	3553

SPRINGFIELD, ILLINOIS Elev 187 Lat 39.8

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1846	2688	–3	402	487	573	659
Jul	6493	3105	24	0	0	0	0
Yr	4114	3164	12	1421	1908	2458	3088

TABLE C.20 Average Insolation, Temperature, and DD Data (SI units) (*Continued*)

Elevation in meters; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in W/day m^2; TA in degrees C; D10.0, D12.8, D15.6, and D18.3 in degree days C (for these various “base” temperatures).

United States

INDIANAPOLIS, INDIANA — Elev 246 — Lat 39.7

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1565	2108	−2	381	467	553	639
Jul	5698	2811	24	0	0	0	0
Yr	3682	2754	11	1395	1891	2456	3098

SOUTH BEND, INDIANA — Elev 236 — Lat 41.7

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1312	1786	−4	448	534	620	706
Jul	5843	2978	22	0	1	2	3
Yr	3597	2726	9	1729	2269	2888	3590

DES MOINES, IOWA — Elev 294 — Lat 41.5

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1833	2877	−7	527	613	699	786
Jul	6616	3272	24	0	0	0	0
Yr	4146	3360	9	1939	2464	3061	3728

DODGE CITY, KANSAS — Elev 787 — Lat 37.8

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2609	4111	−1	331	417	503	589
Jul	7241	3196	26	0	0	0	0
Yr	4928	3887	13	1184	1656	2192	2803

TOPEKA, KANSAS — Elev 270 — Lat 39.1

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2149	3259	−2	379	465	551	637
Jul	6714	3133	26	0	0	0	0
Yr	4376	3269	12	1292	1764	2298	2913

LEXINGTON, KENTUCKY — Elev 301 — Lat 38.0

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1723	2253	1	295	381	467	553
Jul	5837	2780	24	0	0	0	0
Yr	3852	2814	13	1036	1492	2018	2627

BATON ROUGE, LOUISIANA — Elev 23 — Lat 30.5

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2477	2805	11	50	97	163	251
Jul	5509	2480	28	0	0	0	0
Yr	4354	2881	19	129	294	559	928

NEW ORLEANS, LOUISIANA — Elev 3 — Lat 30.0

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2634	2997	12	41	83	140	224
Jul	5720	2527	28	0	0	0	0
Yr	4537	2975	20	109	258	493	814

SHREVEPORT, LOUISIANA — Elev 79 — Lat 32.5

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2404	2903	8	86	147	224	307
Jul	6354	2726	28	0	0	0	0
Yr	4505	3070	19	238	462	786	1204

PORTLAND, MAINE — Elev 19 — Lat 43.6

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1420	2174	−6	491	577	663	749
Jul	5234	2821	20	0	1	3	15
Yr	3319	2704	7	2027	2643	3355	4166

DETROIT, MICHIGAN — Elev 191 — Lat 42.4

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1316	1846	−3	422	508	594	681
Jul	5789	3000	23	0	0	0	0
Yr	3540	2742	10	1628	2161	2770	3460

SAULT STE. MARIE, MICHIGAN — Elev 221 — Lat 46.5

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1025	1552	−10	617	703	789	875
Jul	5789	3297	18	1	4	18	53
Yr	3294	2716	4	2761	3443	4226	5107

MINNEAPOLIS, MINNESOTA — Elev 255 — Lat 44.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1464	2423	−11	651	737	823	909
Jul	6215	3379	22	0	1	3	6
Yr	3698	3142	7	2547	3128	3791	4533

MERIDIAN, MISSISSIPPI — Elev 94 — Lat 32.3

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2347	2786	8	91	152	229	319
Jul	5752	2571	27	0	0	0	0
Yr	4326	2944	18	283	531	879	1327

SAINT LOUIS, MISSOURI — Elev 172 — Lat 38.7

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1978	2833	−1	323	408	494	581
Jul	6465	3026	26	0	0	0	0
Yr	4193	3174	13	1089	1534	2048	2639

SPRINGFIELD, MISSOURI — Elev 387 — Lat 37.2

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2158	3016	1	297	381	467	553
Jul	6509	2953	26	0	0	0	0
Yr	4303	3190	13	1027	1454	1957	2539

HELENA, MONTANA — Elev 1188 — Lat 46.6

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1322	2268	−8	549	636	722	808
Jul	7364	4139	20	1	2	7	18
Yr	3994	3578	6	2306	2968	3716	4550

NORTH OMAHA, NEBRASKA — Elev 404 — Lat 41.4

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2000	3262	−7	513	599	686	772
Jul	6644	3275	24	0	1	2	4
Yr	4174	3401	9	1872	2394	2989	3667

ELY, NEVADA — Elev 1906 — Lat 39.3

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2584	4354	−4	454	541	627	713
Jul	7720	3452	19	0	1	6	13
Yr	5285	4389	7	2064	2734	3495	4341

LAS VEGAS, NEVADA — Elev 664 — Lat 36.1

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3086	4900	7	120	192	274	358
Jul	8165	3278	32	0	0	0	0
Yr	5887	4515	19	351	627	993	1445

RENO, NEVADA — Elev 1341 — Lat 39.5

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2524	4243	0	312	398	484	570
Jul	8493	3682	21	0	1	3	9
Yr	5565	4540	9	1273	1858	2550	3346

ALBUQUERQUE, NEW MEXICO — Elev 1619 — Lat 35.0

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3205	4928	2	255	341	427	513
Jul	7853	3139	26	0	0	0	0
Yr	5774	4351	14	832	1273	1787	2384

TABLE C.20 Average Insolation, Temperature, and DD Data (SI units) (*Continued*)

Elevation in meters; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in W/day m^2; TA in degrees C; D10.0, D12.8, D15.6, and D18.3 in degree days C (for these various "base" temperatures).

United States

LOS ALAMOS, NEW MEXICO — Elev 2249 — Lat 35.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2817	4228	–2	361	447	532	618
Jul	6471	2881	20	0	0	0	0
Yr	4982	3925	9	1568	2139	2802	3576

BUFFALO, NEW YORK — Elev 215 — Lat 42.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1101	1467	–4	453	539	625	711
Jul	5603	2950	21	0	0	2	7
Yr	3272	2461	8	1846	2424	3084	3848

NEW YORK, NEW YORK — Elev 57 — Lat 40.8

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1578	2234	0	307	393	479	565
Jul	5326	2716	25	0	0	0	0
Yr	3474	2679	13	1073	1533	2076	2693

SYRACUSE, NEW YORK — Elev 124 — Lat 43.1

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1215	1697	–4	454	541	627	713
Jul	5546	2937	22	0	1	2	6
Yr	3272	2496	9	1786	2343	2981	3710

ALBANY, NEW YORK — Elev 89 — Lat 42.7

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1439	2126	–6	491	577	663	749
Jul	5442	2865	22	0	1	2	5
Yr	3370	2660	9	1902	2460	3103	3827

CHARLOTTE, NORTH CAROLINA — Elev 234 — Lat 35.2

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2268	2978	6	142	223	308	394
Jul	5777	2653	26	0	0	0	0
Yr	4347	3095	16	460	806	1254	1788

RALEIGH-DURHAM, NORTH CAROLINA — Elev 134 — Lat 35.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2190	2915	5	167	251	336	422
Jul	5603	2625	26	0	0	0	0
Yr	4092	3013	15	550	922	1394	1952

BISMARCK, NORTH DAKOTA — Elev 502 — Lat 46.8

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1473	2672	–13	720	806	892	978
Jul	6891	3915	22	0	1	4	10
Yr	3947	3612	5	2908	3536	4237	5024

FARGO, NORTH DAKOTA — Elev 274 — Lat 46.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1309	2272	–14	759	846	932	1018
Jul	6689	3818	22	0	1	3	7
Yr	3805	3392	5	3047	3671	4366	5151

CINCINNATI, OHIO — Elev 271 — Lat 39.1

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1578	2079	–1	326	412	498	584
Jul	5588	2742	24	0	1	2	5
Yr	3660	2707	12	1176	1652	2195	2817

CLEVELAND, OHIO — Elev 245 — Lat 41.4

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1224	1600	–3	398	484	570	656
Jul	5767	2931	22	0	1	2	5
Yr	3448	2549	10	1558	2093	2711	3419

COLUMBUS, OHIO — Elev 254 — Lat 40.0

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1448	1912	–2	372	458	544	631
Jul	5537	2764	23	0	0	0	0
Yr	3559	2631	11	1402	1910	2495	3168

OKLAHOMA CITY, OKLAHOMA — Elev 397 — Lat 35.4

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2527	3515	3	229	314	399	486
Jul	6714	2918	28	0	0	0	0
Yr	4616	3385	16	684	1057	1519	2053

MEDFORD, OREGON — Elev 396 — Lat 42.4

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1284	1783	3	232	317	403	489
Jul	7809	3808	22	0	1	2	6
Yr	4278	3259	12	876	1392	2012	2739

SALEM, OREGON — Elev 61 — Lat 44.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1047	1486	4	193	279	365	451
Jul	6758	3641	19	0	1	4	24
Yr	3565	2830	11	703	1233	1895	2696

HARRISBURG, PENNSYLVANIA — Elev 106 — Lat 40.2

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1691	2407	–1	343	429	515	601
Jul	5565	2786	24	0	0	0	0
Yr	3635	2798	12	1234	1718	2270	2902

PHILADELPHIA, PENNSYLVANIA — Elev 9 — Lat 39.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1751	2499	0	305	391	477	563
Jul	5546	2764	25	0	0	0	0
Yr	3691	2855	13	1075	1542	2083	2703

PITTSBURGH, PENNSYLVANIA — Elev 373 — Lat 40.5

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1338	1745	–2	377	463	549	636
Jul	5329	2704	22	0	1	2	4
Yr	3379	2502	10	1464	1986	2594	3294

PROVIDENCE, RHODE ISLAND — Elev 19 — Lat 41.7

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1596	2366	–2	372	458	544	631
Jul	5348	2770	22	0	0	0	0
Yr	3515	2789	10	1426	1968	2594	3318

CHARLESTON, SOUTH CAROLINA — Elev 12 — Lat 32.9

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2347	2852	9	67	123	200	289
Jul	5676	2565	27	0	0	0	0
Yr	4247	2966	18	200	420	753	1192

RAPID CITY, SOUTH DAKOTA — Elev 966 — Lat 44.0

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1710	2928	–6	484	570	656	742
Jul	7014	3663	23	1	1	4	7
Yr	4240	3713	8	2045	2638	3314	4069

KNOXVILLE, TENNESSEE — Elev 299 — Lat 35.8

	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1959	2477	5	168	249	334	420
Jul	5692	2647	26	0	0	0	0
Yr	4023	2868	16	566	928	1391	1932

TABLE C.20 Average Insolation, Temperature, and DD Data (SI units) (*Continued*)

Elevation in meters; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in W/day m2; TA in degrees C; D10.0, D12.8, D15.6, and D18.3 in degree days C (for these various "base" temperatures).

United States

MEMPHIS, TENNESSEE					Elev 87		Lat 35.0
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2155	2745	5	173	253	337	422
Jul	6222	2773	28	0	0	0	0
Yr	4316	3045	17	549	882	1309	1793

NASHVILLE, TENNESSEE					Elev 180		Lat 36.1
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1830	2275	3	205	288	374	460
Jul	5966	2742	27	0	0	0	0
Yr	4013	2811	15	664	1041	1511	2053

AUSTIN, TEXAS					Elev 189		Lat 30.3
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2726	3180	10	64	115	185	268
Jul	6641	2729	29	0	0	0	0
Yr	4663	3073	20	161	334	604	965

BROWNSVILLE, TEXAS					Elev 6		Lat 25.9
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2881	2912	16	10	28	64	125
Jul	6979	2735	29	0	0	0	0
Yr	4890	2893	23	24	71	181	361

DALLAS, TEXAS					Elev 149		Lat 32.8
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2590	3265	7	105	173	254	338
Jul	6695	2808	30	0	0	0	0
Yr	4638	3199	19	281	524	857	1272

EL PASO, TEXAS					Elev 1194		Lat 31.8
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3549	4960	7	117	197	283	368
Jul	7730	2947	28	0	0	0	0
Yr	5998	4187	17	312	612	1006	1488

HOUSTON, TEXAS					Elev 33		Lat 30.0
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2436	2688	11	39	83	146	231
Jul	5767	2540	28	0	0	0	0
Yr	4269	2789	21	89	227	458	797

LUBBOCK, TEXAS					Elev 988		Lat 33.6
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	3253	4723	4	191	274	360	446
Jul	7610	3016	27	0	0	0	0
Yr	5578	4035	16	594	966	1434	1969

SAN ANTONIO, TEXAS					Elev 242		Lat 29.5
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2824	3237	11	52	99	168	251
Jul	6692	2723	29	0	0	0	0
Yr	4736	3070	21	118	272	523	872

BRYCE CANYON, UTAH					Elev 2313		Lat 37.7
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2884	4767	–7	520	606	692	778
Jul	7648	3294	17	1	4	26	71
Yr	5496	4430	4	2607	3392	4264	5074

SALT LAKE CITY, UTAH					Elev 1288		Lat 40.8
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2016	3209	–2	379	465	551	637
Jul	8171	3742	25	0	0	0	0
Yr	5067	4105	11	1471	2007	2625	3324

BURLINGTON, VERMONT					Elev 104		Lat 44.5
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1215	1805	–8	572	658	744	830
Jul	5430	2969	21	0	1	2	11
Yr	3228	2571	7	2301	2906	3591	4376

NORFOLK, VIRGINIA					Elev 9		Lat 36.9
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2139	2940	5	167	250	336	417
Jul	5846	2739	26	0	0	0	0
Yr	4187	3123	15	541	914	1383	1938

RICHMOND, VIRGINIA					Elev 50		Lat 37.5
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1994	2723	3	217	302	388	474
Jul	5597	2679	26	0	0	0	0
Yr	3944	2953	14	720	1123	1616	2188

ROANOKE, VIRGINIA					Elev 358		Lat 37.3
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	2082	2874	2	235	321	462	493
Jul	5666	2694	24	0	0	0	0
Yr	4010	3022	13	826	1265	1784	2393

SEATTLE-TACOMA, WASHINGTON					Elev 122		Lat 47.4
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	827	1193	3	204	289	376	462
Jul	7092	4098	18	0	1	9	44
Yr	3332	2704	11	770	1329	2034	2881

SPOKANE, WASHINGTON					Elev 721		Lat 47.6
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	994	1565	–4	424	510	596	682
Jul	7436	4316	21	0	1	4	12
Yr	3871	3370	8	1701	2306	3006	3797

CHARLESTON, WEST VIRGINIA					Elev 290		Lat 38.4
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1571	2013	2	268	353	439	528
Jul	5307	2609	24	0	0	0	0
Yr	3549	2593	13	959	1411	1938	2550

MADISON, WISCONSIN					Elev 262		Lat 43.1
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1625	2593	–8	572	658	744	830
Jul	6102	3183	21	0	1	3	8
Yr	3764	3086	7	2270	2857	3529	4294

MILWAUKEE, WISCONSIN					Elev 211		Lat 42.9
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1511	2306	–7	527	613	699	786
Jul	6190	3209	21	0	1	2	8
Yr	3767	3019	8	2097	2685	3358	4136

SHERIDAN, WYOMING					Elev 1209		Lat 44.8
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1631	2840	–6	499	586	672	758
Jul	7348	3903	21	1	1	5	16
Yr	4206	3691	7	2144	2773	3488	4282

TABLE C.20 Average Insolation, Temperature, and DD Data (SI units) (*Continued*)

Elevation in meters; latitude in degrees north latitude; HS (horizontal surface) and VS (vertical surface) insolation in W/day m2; TA in degrees C; D10.0, D12.8, D15.6, and D18.3 in degree days C (for these various “base” temperatures).

Canada

EDMONTON, ALBERTA						Elev 677	Lat 53.6
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1022	2354	−16	789	874	960	1046
Jul	6237	4348	17	1	4	21	65
Yr	3515	3802	2	3509	4202	5009	5917

SUFFIELD, ALBERTA						Elev 777	Lat 50.3
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1366	2956	−14	741	826	911	997
Jul	6856	4344	19	0	1	6	27
Yr	3909	4004	4	3056	3687	4402	5218

VANCOUVER, BRITISH COLUMBIA						Elev 94	Lat 37.5
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	801	1246	3	236	318	402	488
Jul	6376	3909	17	0	1	7	46
Yr	3344	2890	10	995	1545	2245	3104

WINNIPEG, MANITOBA						Elev 250	Lat 49.95
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1454	3190	−18	882	967	1052	1137
Jul	6389	3988	19	0	1	5	25
Yr	3754	3783	2	3847	4479	5188	5994

HALIFAX, NOVA SCOTIA						Elev 41	Lat 44.6
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1439	2325	−3	418	500	584	669
Jul	5345	2931	18	0	1	4	32
Yr	3395	2862	8	1921	2500	3192	4006

OTTAWA, ONTARIO						Elev 115	Lat 45.5
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1609	2884	−11	649	733	818	904
Jul	5916	3281	21	0	1	2	13
Yr	3653	3202	6	2729	3314	3977	4738

TORONTO, ONTARIO						Elev 135	Lat 43.7
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1536	2451	−6	495	578	663	749
Jul	6177	3265	21	0	0	2	10
Yr	3695	2991	8	2134	2696	3341	4079

NORMANDIN, QUEBEC						Elev 137	Lat 48.8
	HS	VS	TA	D10.0	D12.8	D15.6	D18.3
Jan	1432	2906	−18	869	955	1041	1127
Jul	5386	3253	17	1	4	22	66
Yr	3445	3322	1	3909	4616	5423	6320

Source: Reprinted by permission from J. D. Balcomb et al., *Passive Solar Design Handbook*, Vol. 3, © 1983, American Solar Energy Society, Inc., Boulder, CO.
The original source provided only I-P units; the conversions to SI units were made by the authors of this book.

TABLE C.21 Coefficient of Utilization from Window without Blinds; Sky Component $E_{xvk}/E_{xhk} = 0.75$

Room Depth/ Window Height	Depth	Window Width/Window Height .5	1	2	3	4	6	8	Infinite
1	10	.824	.864	.870	.873	.875	.879	.880	.883
	30	.547	.711	.777	.789	.793	.798	.799	.801
	50	.355	.526	.635	.659	.666	.669	.670	.672
	70	.243	.386	.505	.538	.548	.544	.545	.547
	90	.185	.304	.418	.451	.464	.444	.446	.447
2	10	.667	.781	.809	.812	.813	.815	.816	.824
	30	.269	.416	.519	.544	.551	.556	.557	.563
	50	.122	.204	.287	.319	.331	.339	.341	.345
	70	.068	.116	.173	.201	.214	.223	.226	.229
	90	.050	.084	.127	.151	.164	.167	.171	.172
3	10	.522	.681	.739	.746	.747	.749	.747	.766
	30	.139	.232	.320	.350	.360	.366	.364	.373
	50	.053	.092	.139	.163	.174	.183	.182	.187
	70	.031	.053	.081	.097	.106	.116	.116	.119
	90	.025	.041	.061	.074	.082	.089	.090	.092
4	10	.405	.576	.658	.670	.673	.675	.674	.707
	30	.075	.134	.197	.224	.235	.243	.243	.255
	50	.028	.050	.078	.094	.104	.112	.114	.119
	70	.018	.031	.048	.059	.065	.073	.074	.078
	90	.016	.026	.040	.048	.053	.059	.061	.064
6	10	.242	.392	.494	.516	.521	.524	.523	.588
	30	.027	.054	.086	.102	.111	.119	.120	.135
	50	.011	.023	.036	.044	.049	.055	.056	.063
	70	.009	.018	.027	.032	.035	.040	.041	.046
	90	.008	.016	.023	.028	.031	.034	.035	.040
8	10	.147	.257	.352	.380	.387	.391	.392	.482
	30	.012	.026	.043	.054	.060	.067	.070	.086
	50	.006	.013	.021	.026	.029	.033	.035	.043
	70	.005	.011	.017	.021	.023	.026	.027	.034
	90	.004	.010	.015	.019	.021	.023	.025	.030
10	10	.092	.168	.248	.275	.284	.290	.291	.395
	30	.006	.014	.026	.032	.036	.041	.044	.059
	50	.003	.008	.014	.017	.019	.022	.024	.032
	70	.003	.007	.012	.014	.016	.018	.019	.026
	90	.003	.006	.011	.013	.015	.016	.017	.024

Source: IES RP-23-1989; reprinted with permission of Illuminating Engineering Society of North America.

TABLE C.22 Coefficient of Utilization from Window without Blinds; Sky Component E_{xvk}/E_{xhk} = 1.00

Room Depth/ Window Height	Depth	Window Width/Window Height .5	1	2	3	4	6	8	Infinite
1	10	.671	.704	.711	.715	.717	.726	.726	.728
	30	.458	.595	.654	.668	.672	.682	.683	.685
	50	.313	.462	.563	.589	.598	.607	.608	.610
	70	.227	.362	.478	.515	.527	.530	.532	.534
	90	.186	.306	.424	.465	.481	.468	.471	.472
2	10	.545	.636	.658	.660	.661	.665	.666	.672
	30	.239	.367	.459	.484	.491	.499	.501	.506
	50	.121	.203	.286	.320	.335	.348	.351	.355
	70	.074	.128	.192	.226	.243	.259	.264	.267
	90	.058	.101	.156	.188	.207	.215	.221	.223
3	10	.431	.561	.607	.613	.614	.616	.615	.631
	30	.133	.223	.306	.337	.348	.357	.357	.366
	50	.058	.103	.155	.183	.197	.211	.213	.218
	70	.037	.064	.098	.119	.132	.147	.150	.154
	90	.030	.051	.079	.098	.110	.122	.126	.129
4	10	.339	.482	.549	.560	.563	.566	.565	.593
	30	.078	.139	.204	.234	.247	.258	.260	.272
	50	.033	.060	.094	.114	.126	.139	.143	.150
	70	.022	.039	.061	.074	.083	.095	.099	.104
	90	.019	.032	.050	.061	.070	.080	.084	.089
6	10	.211	.343	.433	.453	.458	.461	.461	.518
	30	.033	.065	.103	.123	.135	.145	.148	.167
	50	.015	.029	.047	.057	.064	.073	.077	.086
	70	.011	.021	.033	.040	.045	.051	.054	.060
	90	.010	.019	.028	.034	.038	.044	.046	.052
8	10	.135	.238	.326	.353	.362	.366	.367	.452
	30	.016	.034	.058	.072	.080	.090	.094	.116
	50	.008	.017	.027	.034	.039	.045	.048	.059
	70	.006	.013	.021	.026	.028	.032	.035	.043
	90	.005	.012	.019	.023	.025	.029	.031	.038
10	10	.090	.165	.244	.272	.283	.290	.291	.395
	30	.009	.020	.036	.045	.052	.060	.064	.087
	50	.005	.010	.019	.023	.026	.030	.033	.044
	70	.004	.009	.015	.018	.020	.023	.025	.033
	90	.003	.008	.014	.016	.018	.020	.022	.030

Source: IES RP-23-1989; reprinted with permission of Illuminating Engineering Society of North America.

TABLE C.23 Coefficient of Utilization from Window without Blinds; Sky Component E_{xvk}/E_{xhk} = 1.25

Room Depth/ Window Height	Depth	Window Width/Window Height .5	1	2	3	4	6	8	Infinite
1	10	.578	.607	.614	.619	.621	.633	.634	.635
	30	.405	.525	.580	.594	.599	.612	.614	.615
	50	.287	.423	.519	.547	.556	.569	.571	.573
	70	.218	.347	.461	.501	.515	.522	.525	.526
	90	.186	.307	.428	.473	.491	.483	.486	.487
2	10	.472	.549	.566	.569	.570	.574	.575	.581
	30	.221	.337	.422	.447	.456	.465	.467	.472
	50	.120	.202	.285	.321	.337	.353	.357	.361
	70	.078	.136	.204	.242	.261	.281	.287	.290
	90	.064	.112	.174	.211	.233	.244	.251	.253
3	10	.377	.488	.527	.533	.534	.536	.536	.549
	30	.130	.217	.298	.329	.341	.352	.353	.362
	50	.062	.110	.165	.195	.211	.228	.231	.237
	70	.040	.070	.109	.132	.147	.166	.171	.175
	90	.033	.057	.090	.112	.127	.142	.148	.152
4	10	.300	.424	.484	.494	.497	.499	.499	.524
	30	.080	.143	.209	.240	.255	.267	.269	.283
	50	.036	.066	.104	.126	.140	.156	.160	.168
	70	.024	.043	.068	.083	.094	.109	.115	.120
	90	.021	.036	.056	.070	.080	.092	.099	.103
6	10	.193	.314	.395	.415	.420	.423	.423	.476
	30	.036	.071	.113	.136	.149	.161	.165	.186
	50	.017	.033	.053	.065	.074	.084	.089	.100
	70	.012	.024	.037	.045	.050	.058	.061	.069
	90	.011	.021	.031	.038	.043	.049	.053	.060
8	10	.128	.226	.310	.337	.346	.351	.352	.433
	30	.019	.039	.066	.082	.092	.104	.109	.134
	50	.009	.019	.031	.040	.045	.052	.056	.069
	70	.007	.015	.023	.029	.032	.037	.040	.049
	90	.006	.013	.021	.025	.028	.032	.035	.043
10	10	.088	.164	.241	.270	.282	.290	.291	.396
	30	.011	.024	.043	.054	.062	.071	.076	.103
	50	.005	.012	.022	.026	.030	.035	.038	.052
	70	.004	.010	.017	.020	.023	.026	.028	.038
	90	.004	.009	.016	.018	.020	.023	.025	.034

Source: IES RP-23-1989; reprinted with permission of Illuminating Engineering Society of North America.

TABLE C.24 Coefficient of Utilization from Window without Blinds; Sky Component E_{xvk}/E_{xhk} = 1.50

Room Depth/ Window Height	Depth	Window Width/Window Height .5	1	2	3	4	6	8	Infinite
1	10	.503	.528	.536	.541	.544	.557	.558	.559
	30	.359	.464	.514	.528	.534	.549	.550	.552
	50	.261	.384	.471	.499	.508	.524	.526	.527
	70	.204	.325	.432	.470	.485	.497	.499	.500
	90	.179	.295	.412	.456	.475	.474	.477	.478
2	10	.412	.477	.490	.492	.493	.498	.499	.505
	30	.201	.304	.379	.402	.410	.422	.424	.429
	50	.115	.192	.269	.304	.320	.339	.343	.347
	70	.078	.136	.204	.241	.261	.286	.292	.295
	90	.066	.117	.183	.221	.246	.262	.271	.273
3	10	.331	.426	.458	.461	.462	.465	.465	.477
	30	.121	.202	.275	.304	.316	.327	.329	.337
	50	.062	.109	.164	.193	.209	.228	.232	.238
	70	.041	.073	.114	.138	.154	.176	.183	.188
	90	.035	.062	.099	.123	.141	.159	.169	.173
4	10	.265	.372	.422	.430	.433	.435	.435	.456
	30	.077	.137	.199	.229	.243	.256	.259	.272
	50	.037	.069	.107	.130	.144	.161	.167	.175
	70	.026	.046	.073	.089	.101	.119	.126	.132
	90	.022	.039	.063	.078	.090	.106	.114	.120
6	10	.173	.281	.351	.368	.373	.375	.375	.422
	30	.037	.073	.115	.137	.151	.164	.168	.189
	50	.018	.036	.058	.071	.080	.092	.098	.110
	70	.013	.026	.040	.049	.056	.064	.069	.078
	90	.012	.023	.035	.043	.048	.057	.062	.070
8	10	.117	.207	.282	.305	.314	.319	.320	.393
	30	.020	.042	.071	.087	.098	.111	.116	.143
	50	.010	.021	.035	.044	.050	.058	.063	.078
	70	.007	.016	.026	.032	.036	.041	.045	.055
	90	.076	.014	.023	.028	.031	.036	.040	.049
10	10	.082	.153	.224	.250	.262	.269	.271	.368
	30	.012	.026	.047	.059	.068	.078	.084	.114
	50	.006	.014	.024	.030	.034	.040	.044	.060
	70	.005	.011	.019	.022	.025	.029	.032	.043
	90	.004	.010	.017	.020	.023	.026	.028	.038

Source: IES RP-23-1989; reprinted with permission of Illuminating Engineering Society of North America.

TABLE C.25 Coefficient of Utilization from Window without Blinds; Sky Component E_{xvk}/E_{xhk} = 1.75

Room Depth/ Window Height	Depth	Window Width/Window Height							
		.5	1	2	3	4	6	8	Infinite
1	10	.435	.457	.465	.471	.474	.486	.488	.489
	30	.317	.407	.452	.466	.471	.486	.488	.489
	50	.234	.343	.422	.447	.456	.472	.475	.476
	70	.187	.297	.395	.430	.445	.458	.461	.462
	90	.168	.276	.384	.426	.444	.447	.450	.451
2	10	.357	.412	.422	.424	.424	.430	.431	.436
	30	.180	.271	.335	.356	.363	.375	.378	.381
	50	.106	.177	.246	.278	.293	.313	.318	.321
	70	.074	.130	.194	.229	.249	.274	.282	.284
	90	.065	.116	.181	.219	.244	.264	.273	.276
3	10	.288	.369	.394	.397	.397	.400	.401	.411
	30	.110	.183	.247	.272	.282	.294	.296	.304
	50	.058	.104	.154	.181	.196	.215	.221	.226
	70	.040	.072	.112	.136	.152	.176	.184	.188
	90	.035	.063	.101	.126	.144	.166	.177	.182
4	10	.232	.324	.365	.371	.373	.375	.375	.394
	30	.071	.127	.183	.209	.222	.235	.238	.250
	50	.036	.067	.104	.125	.139	.157	.163	.171
	70	.025	.046	.072	.089	.101	.119	.127	.134
	90	.022	.041	.065	.082	.095	.114	.124	.130
6	10	.153	.247	.307	.320	.324	.326	.327	.367
	30	.035	.070	.109	.130	.143	.155	.160	.180
	50	.018	.036	.058	.071	.080	.091	.098	.110
	70	.013	.026	.041	.051	.058	.067	.073	.082
	90	.012	.023	.037	.046	.052	.062	.069	.078
8	10	.104	.184	.249	.269	.276	.281	.282	.346
	30	.020	.042	.070	.086	.096	.109	.115	.141
	50	.010	.022	.036	.046	.052	.060	.066	.081
	70	.008	.017	.027	.033	.038	.044	.048	.059
	90	.007	.015	.024	.030	.034	.040	.044	.054
10	10	.074	.138	.201	.223	.233	.240	.242	.328
	30	.012	.027	.048	.059	.067	.078	.084	.114
	50	.006	.014	.026	.032	.036	.043	.047	.064
	70	.005	.011	.020	.024	.027	.031	.034	.046
	90	.004	.010	.018	.022	.024	.028	.031	.042

Source: IES RP-23-1989; reprinted with permission of Illuminating Engineering Society of North America.

TABLE C.26 Coefficient of Utilization from Window without Blinds; Ground Component

Room Depth/ Window Height	Depth	*Window Width/Window Height* .5	1	2	3	4	6	8	Infinite
1	10	.105	.137	.177	.197	.207	.208	.210	.211
	30	.116	.157	.203	.225	.235	.241	.243	.244
	50	.110	.165	.217	.241	.252	.267	.269	.270
	70	.101	.162	.217	.243	.253	.283	.285	.286
	90	.091	.146	.199	.230	.239	.290	.292	.293
2	10	.095	.124	.160	.178	.186	.186	.189	.191
	30	.082	.132	.179	.201	.212	.219	.222	.225
	50	.062	.113	.165	.189	.202	.214	.218	.220
	70	.051	.093	.141	.165	.179	.194	.198	.200
	90	.045	.079	.118	.140	.153	.179	.183	.185
3	10	.088	.120	.157	.175	.183	.185	.163	.167
	30	.059	.107	.154	.176	.187	.198	.193	.198
	50	.039	.074	.114	.134	.146	.157	.163	.170
	70	.031	.055	.085	.101	.111	.122	.127	.130
	90	.028	.047	.070	.083	.092	.107	.113	.115
4	10	.073	.113	.154	.174	.183	.187	.176	.184
	30	.040	.082	.127	.148	.159	.170	.177	.185
	50	.025	.049	.078	.094	.103	.113	.117	.123
	70	.020	.036	.054	.065	.071	.079	.083	.087
	90	.019	.032	.046	.054	.060	.069	.073	.076
6	10	.056	.106	.143	.164	.175	.184	.173	.194
	30	.021	.050	.081	.098	.107	.117	.123	.138
	50	.013	.027	.041	.049	.054	.060	.064	.072
	70	.011	.021	.029	.033	.035	.039	.041	.046
	90	.011	.020	.026	.030	.032	.035	.037	.042
8	10	.036	.082	.122	.143	.156	.166	.170	.208
	30	.011	.029	.050	.062	.070	.078	.082	.101
	50	.007	.016	.024	.028	.031	.035	.038	.046
	70	.006	.013	.018	.020	.021	.023	.025	.030
	90	.006	.013	.017	.019	.020	.022	.023	.028
10	10	.024	.061	.109	.120	.131	.144	.147	.200
	30	.006	.017	.034	.040	.046	.053	.056	.076
	50	.004	.010	.016	.018	.020	.023	.024	.033
	70	.004	.009	.013	.014	.015	.016	.016	.022
	90	.004	.009	.013	.013	.014	.015	.016	.021

Source: IES RP-23-1989; reprinted with permission of Illuminating Engineering Society of North America.

Table C.27 Reflectances of Daylighting Modeling Materials

Materials	Number	Reflectance (%)
Crescent Board Color		
Raven Black	989	6.7
Newport Blue	977	9.1
Wine	907 A	12.6
Williamsburg Green	988	12.7
Volcano Blue	1081	15.5
Russet	996	15.7
Las Cruces Purple	1076	16.1
Marine Blue	1082	16.5
Madeira Red	1075	19.4
Avocado	1084	21.6
Persimmon	1087	26.4
Gibraltar Grey	1074	28.5
Burnt Orange	1077	33.5
Moss Point Green	1001	35.0
Bar Harbor Grey	976	38.5
Bimini Blue	1080	43.3
Mist Grey	1002	43.5
Suntan	1062	45.8
Stone Grey	975	48.5
French Blue	972	54.2
Cameo Rose	973	56.0
Biscay Blue	1073	56.0
Sauterne	1089	59.4
Lime	910 A	59.7
Sandstone	1061	61.0
Madagascar Pink	1078	73.7
Mist	1088	76.3
Daffodil	971	88.8
Yellow	902 A	93.1
Mat Board		
Arctic White	3297	91.4
Linen Board		
Cream Linen	2961 A	91.0
French Grey	2962 A	76.0
Museum Board		
2-ply White	1150	96.5
2-ply Antique	1157	91.5
2-ply Cream	1152	94.2

Source: Technical Reference Sheet; The Lighting Design Lab, Seattle, WA.

APPENDIX D

Solar Geometry

This appendix provides information on various aspects of solar geometry, including three sets of sunpath diagrams (sunpeg charts, horizontal projection charts, and vertical projection charts).

- Solar altitude and azimuth data for 30, 34, 38, 42, 44, and 48°N latitudes (Table D.1)
- Sunpeg charts for 28, 32, 36, 40, 44, 48, and 52°N latitudes (Fig. D.1)
- Horizontal projection (equidistant) sunpath charts for 24, 28, 32, 36, 40, 44, 48, and 52°N latitudes (Fig. D.2)
- Vertical projection sunpath charts for 28, 32, 36, 40, 44, 48, 52, and 56°N latitudes (Fig. D.3)

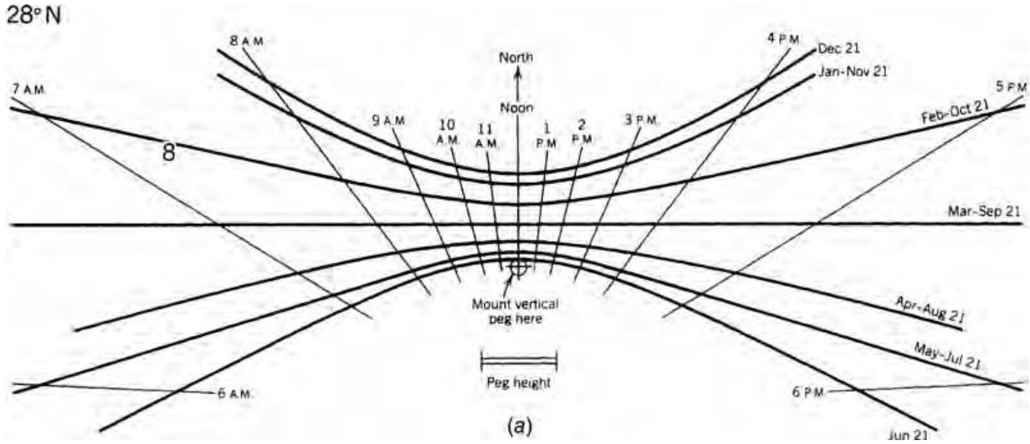
D.1 SOLAR ALTITUDE AND AZIMUTH DATA FOR 30, 34, 38, 42, 44, AND 48ºN LATITUDES

TABLE D.1 Typical Solar Altitude and Azimuth Data as a Function of Date and Time of Day

Latitude (°N)		Date	Solar Time[a] AM: 6 / PM: 6	7 / 5	8 / 4	9 / 3	10 / 2	11 / 1	Noon
30	Altitude	June 21	12	24	37	50	63	75	83
		Mar–Sept 21	—	13	26	38	49	57	60
		Dec 21	—	—	12	21	29	35	37
	Azimuth	June 21	111	104	99	92	84	67	0
		Mar–Sept 21	90	83	74	64	49	28	0
		Dec 21	—	60	54	44	32	17	0
34	Altitude	June 21	13	25	37	50	62	74	79
		Mar–Sept 21	—	12	25	36	46	53	56
		Dec 21	—	—	9	18	26	31	33
	Azimuth	June 21	110	103	95	90	78	58	0
		Mar–Sept 21	90	82	72	61	46	26	0
		Dec 21	—	—	54	43	30	16	0
38	Altitude	June 21	14	26	37	49	61	71	75
		Mar–Sept 21	—	12	23	34	43	50	52
		Dec 21	—	—	7	16	23	27	28
	Azimuth	June 21	109	101	90	83	70	46	0
		Mar–Sept 21	90	81	71	58	43	24	0
		Dec 21	—	—	54	43	30	16	0
42	Altitude	June 21	16	26	38	49	60	68	71
		Mar–Sept 21	—	11	22	32	40	46	48
		Dec 21	—	—	4	13	19	23	25
	Azimuth	June 21	108	99	89	78	63	39	0
		Mar–Sept 21	90	80	69	56	41	22	0
		Dec 21	—	—	53	42	29	15	0
46	Altitude	June 21	17	27	37	48	57	65	67
		Mar–Sept 21	—	10	20	30	37	42	44
		Dec 21	—	—	2	10	15	20	21
	Azimuth	June 21	107	97	88	74	58	34	0
		Mar–Sept 21	90	79	67	54	39	21	0
		Dec 21	—	—	52	41	28	14	0
48	Altitude	June 21	17	27	37	47	56	63	65
		Mar–Sept 21	—	10	20	29	36	40	42
		Dec 21	—	—	1	8	14	17	19
	Azimuth	June 21	106	95	85	72	55	31	0
		Mar–Sept 21	90	79	67	53	38	20	0
		Dec 21	—	—	52	41	28	14	0

[a]Solar time and clock time do not usually coincide. They are related by the equation of time (see Section 6.2).

D.2 SUNPEG CHARTS FOR 28, 32, 36, 40, 44, 48, AND 52ºN LATITUDES



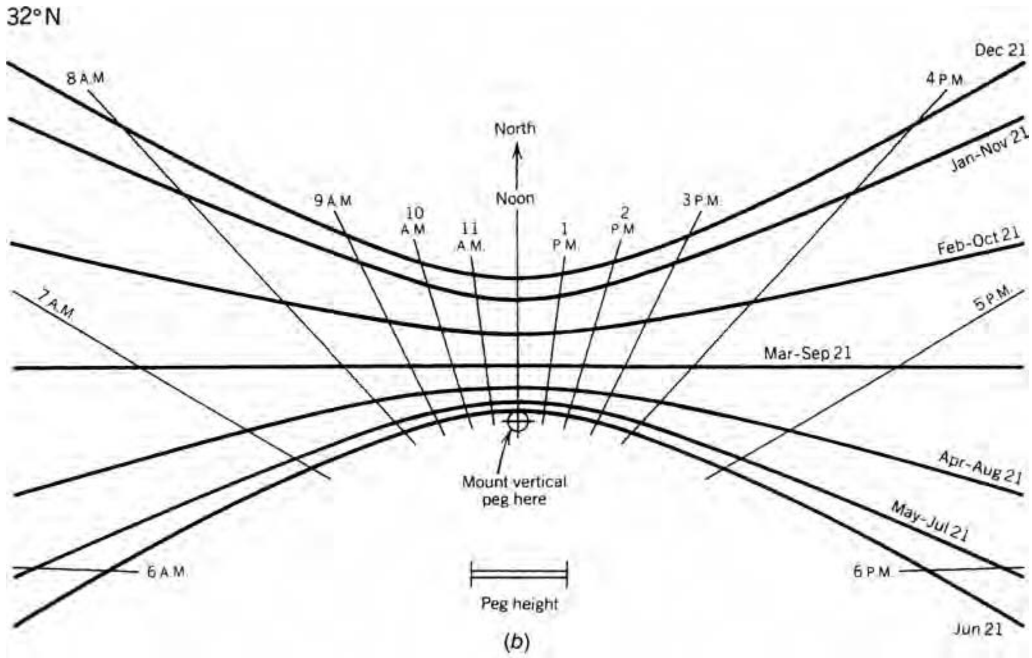
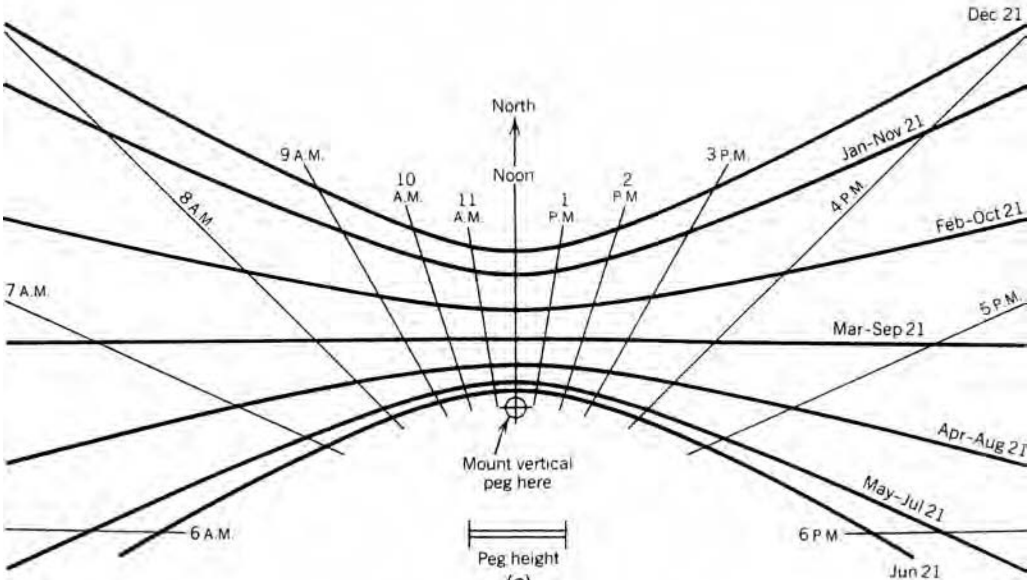


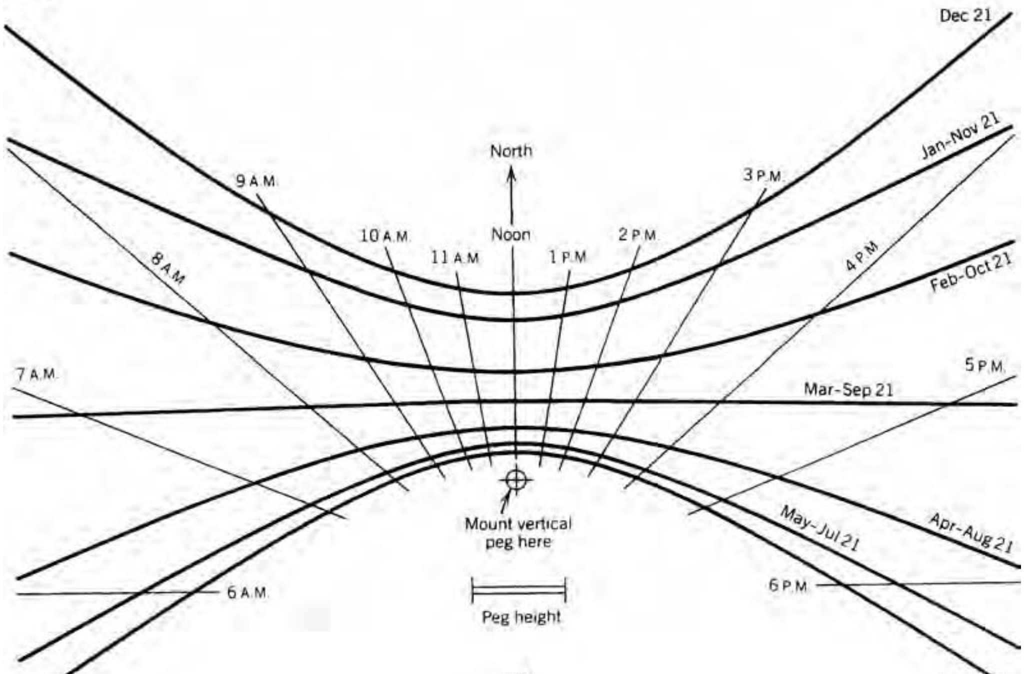
Fig. D.1 *(a–g) Sunpeg shadow charts. These charts show the exact positions of solar radiation and shadow on a model of any scale, on any date, at any time of day between shortly after sunrise and shortly before sunset. Latitudes as indicated in the upper-left corner of each chart. See Chapter 6 for instructions on the use of these charts.*

36° N



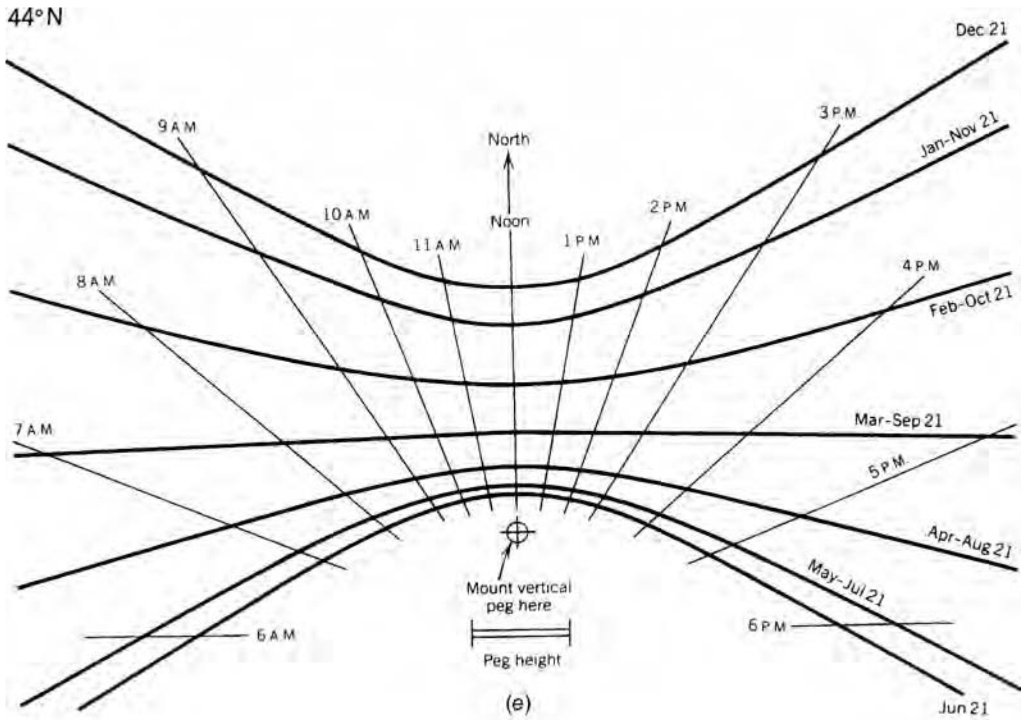
(*c*)

40° N



(*d*)

Fig. D.1 *(continued)*



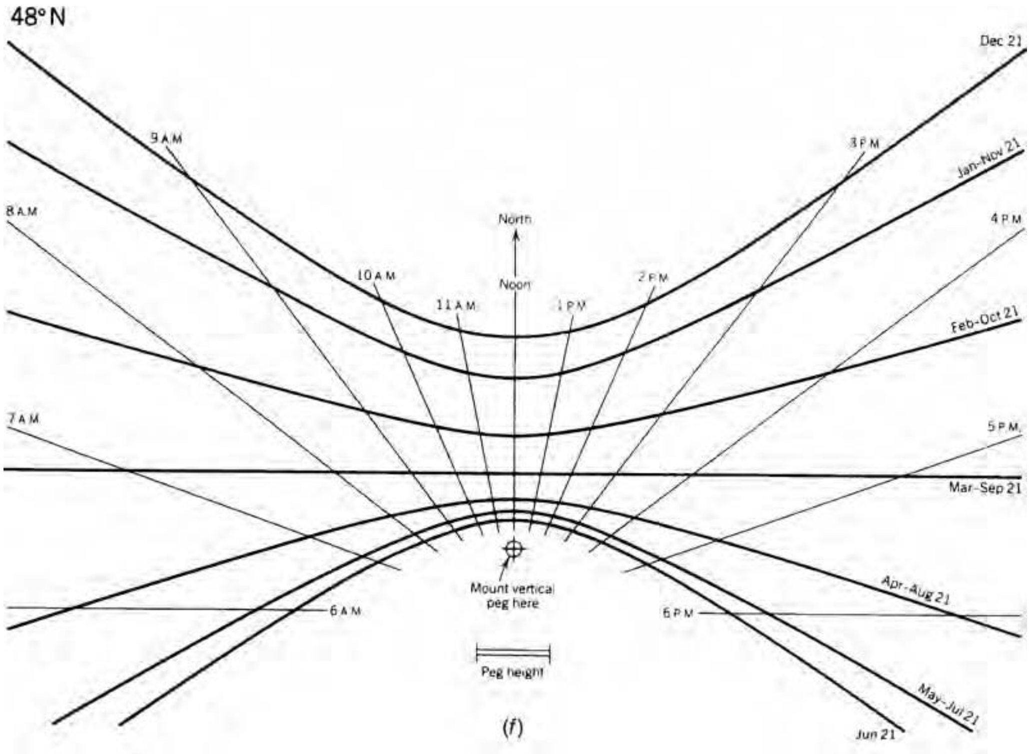


Fig. D.1 *(continued)*

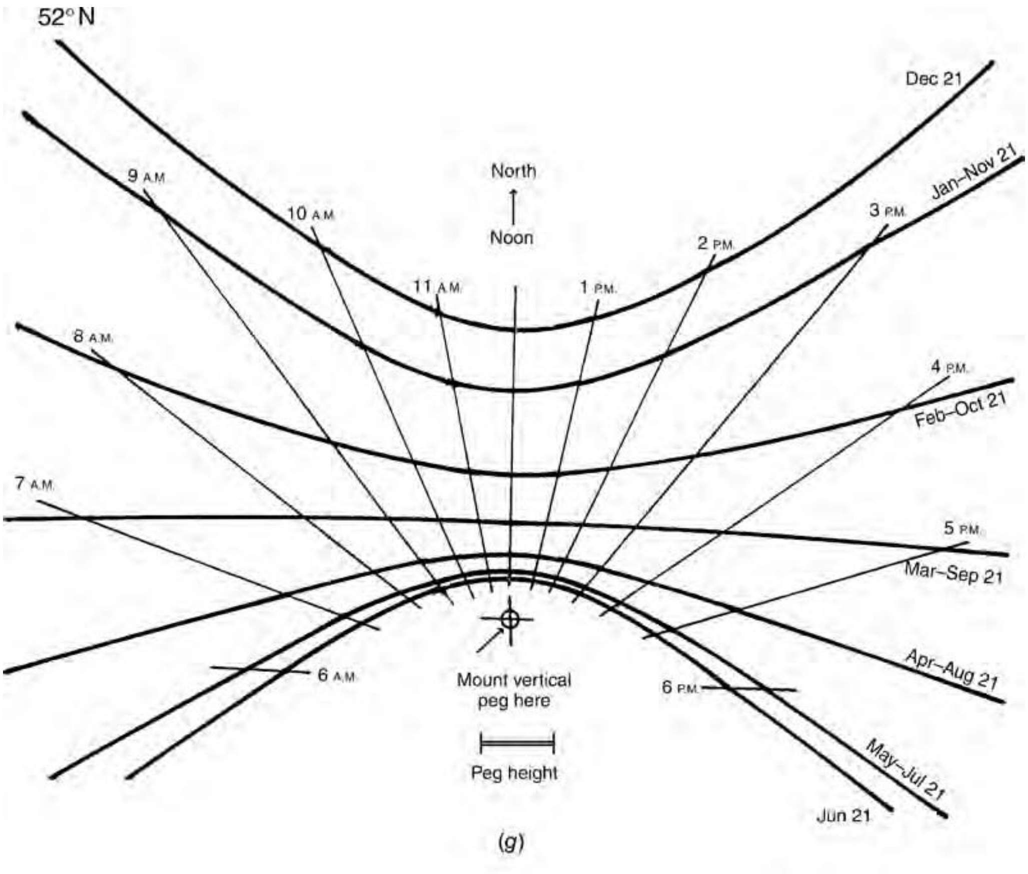
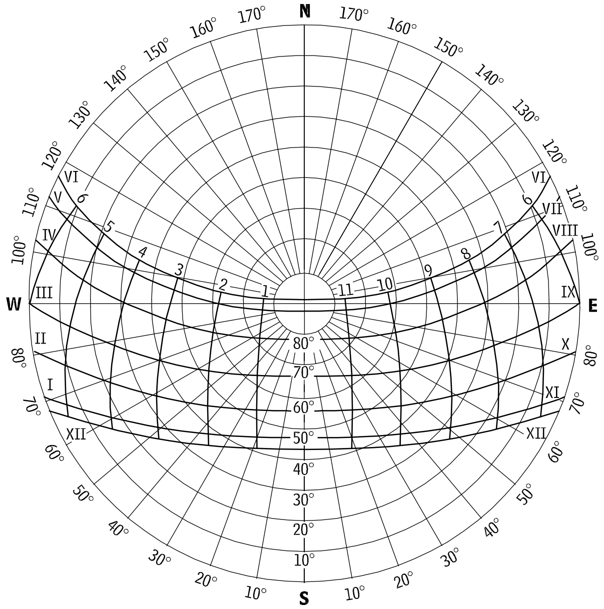
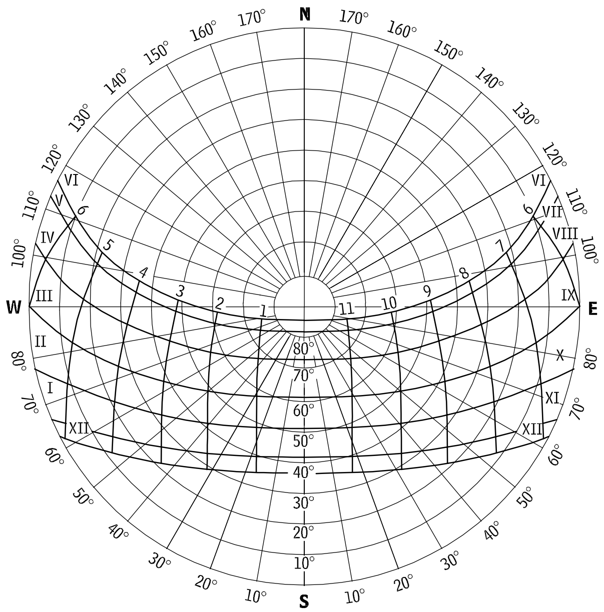


Fig. D.1 *(continued)*

D.3 HORIZONTAL PROJECTION (EQUIDISTANT) SUNPATH CHARTS FOR 24, 28, 32, 36, 40, 44, 48, AND 52ºN LATITUDES

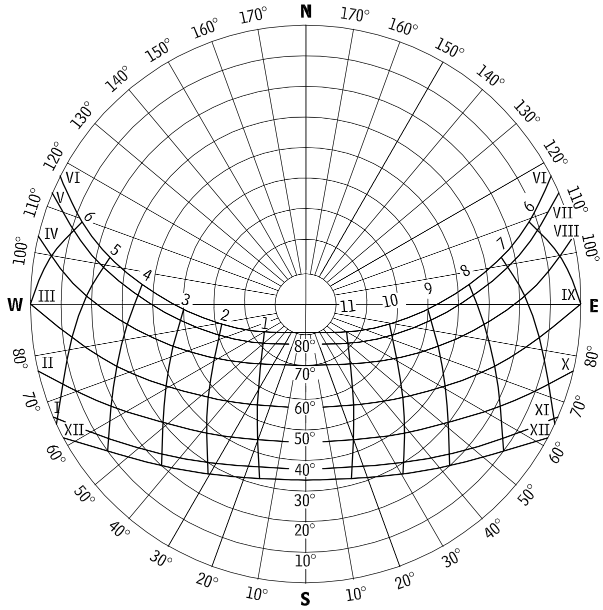


(*a*) **24° N LATITUDE**

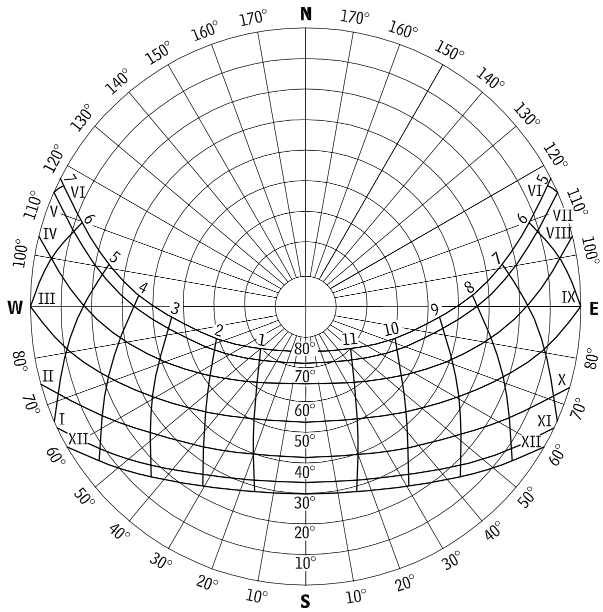


(*b*) **28° N LATITUDE**

Fig. D.2 *(a–h) Set of horizontal projection (equidistant) sunpath charts at 4º latitude intervals. Latitudes as indicated below each chart. (Reprinted with permission from* Architectural Graphic Standards, *11th ed.; © 2007 by John Wiley & Sons, Publishers.)*

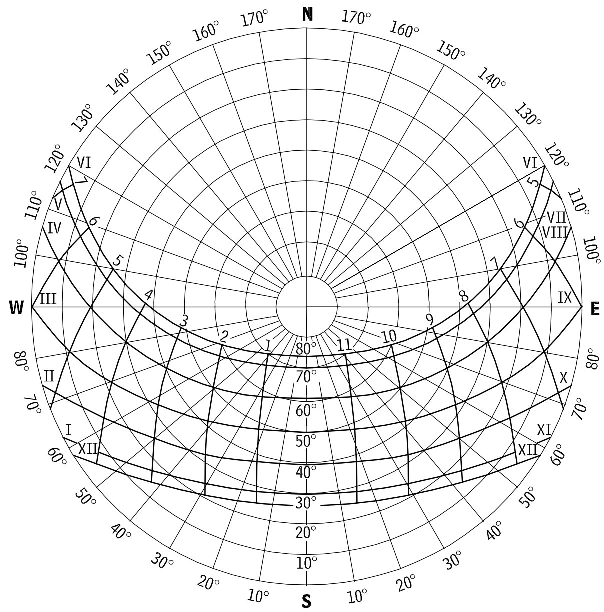


(*c*) **32° N LATITUDE**

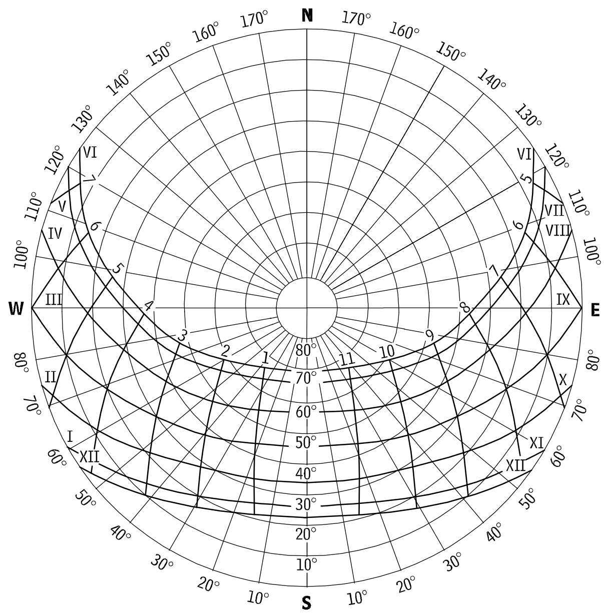


(*d*) **36° N LATITUDE**

Fig. D.2 *(continued)*

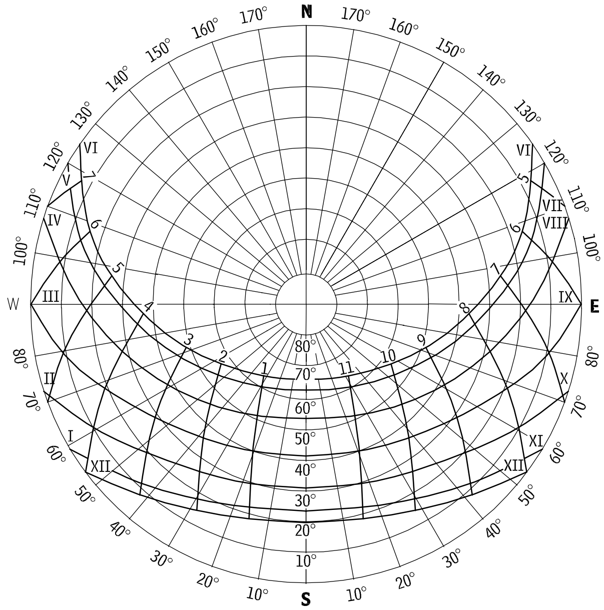


(*e*) **40° N LATITUDE**

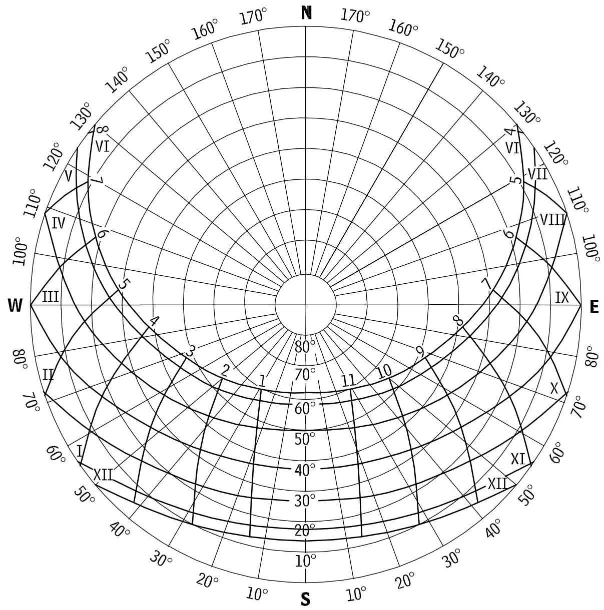


(*f*) **44° N LATITUDE**

Fig. D.2 *(continued)*



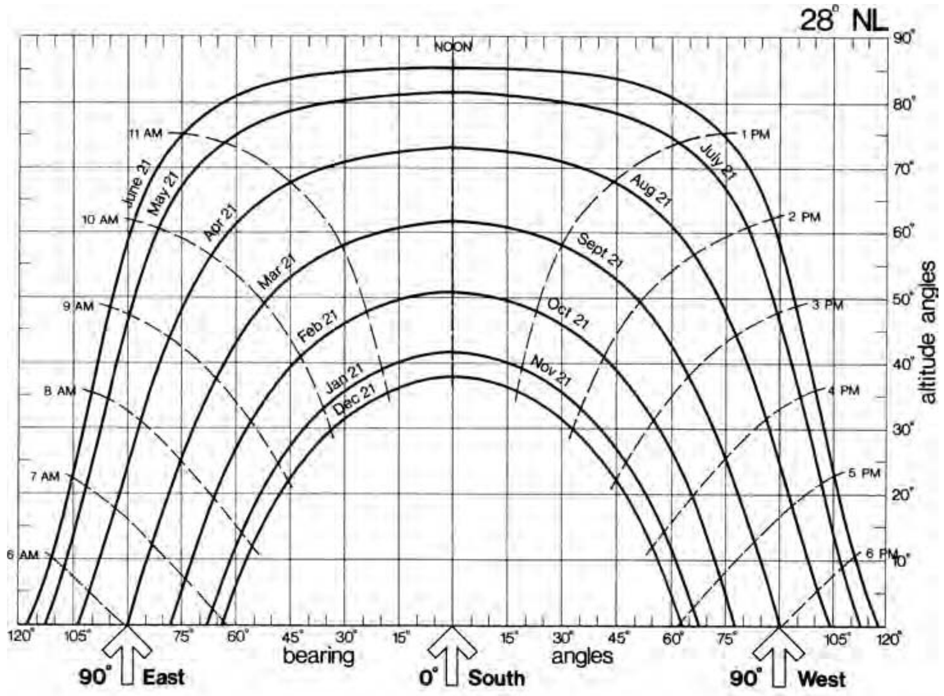
(*g*) **48° N LATITUDE**



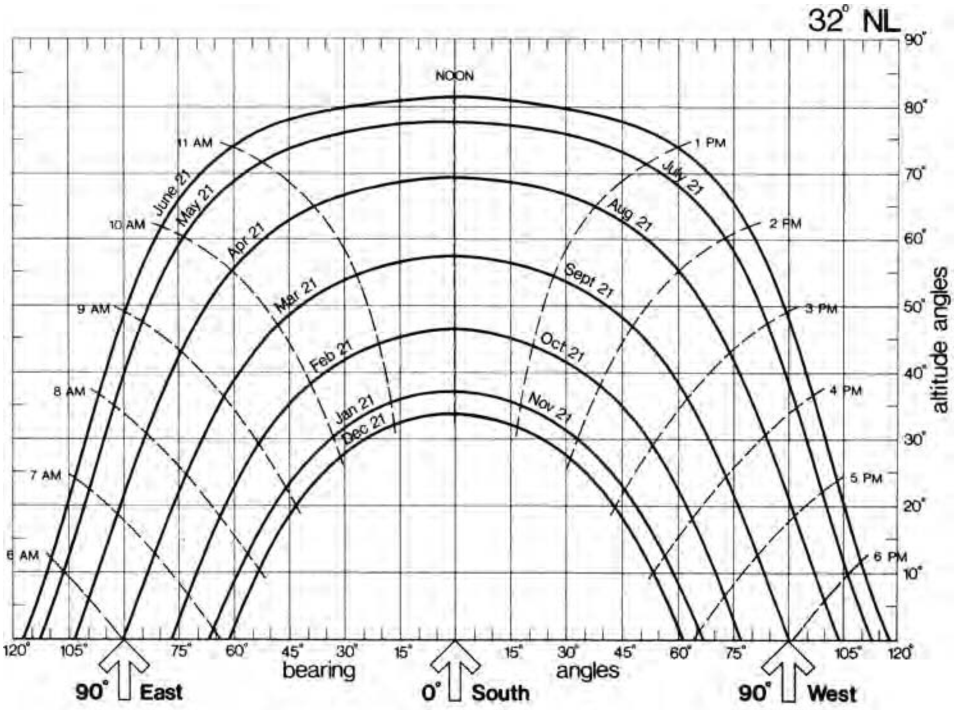
(*h*) **52° N LATITUDE**

Fig. D.2 *(continued)*

D.4 VERTICAL PROJECTION SUNPATH CHARTS FOR 28, 32, 36, 40, 44, 48, 52, AND 56°N LATITUDES

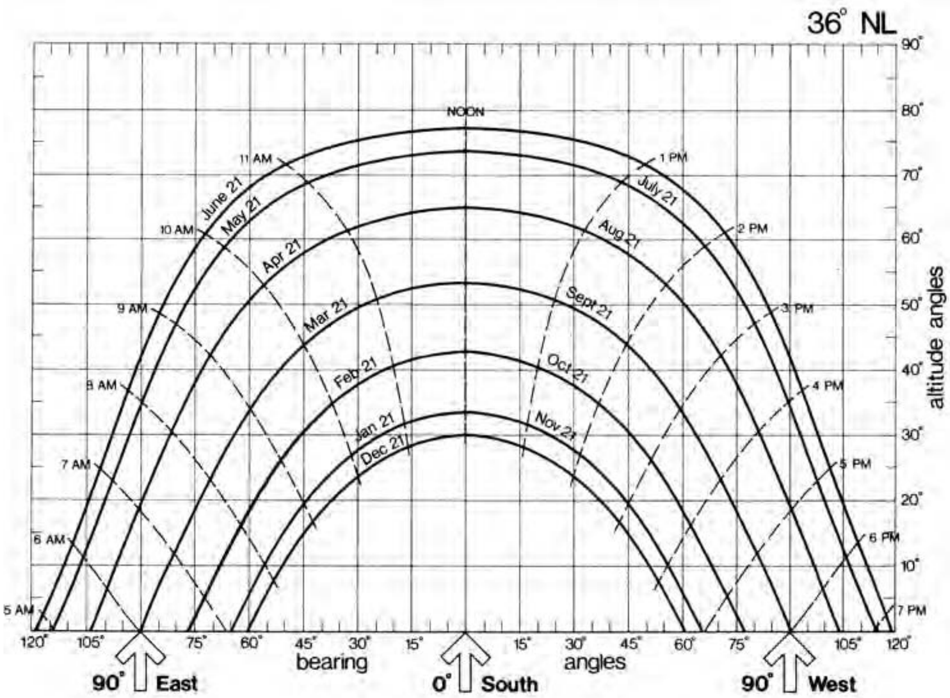


(a)

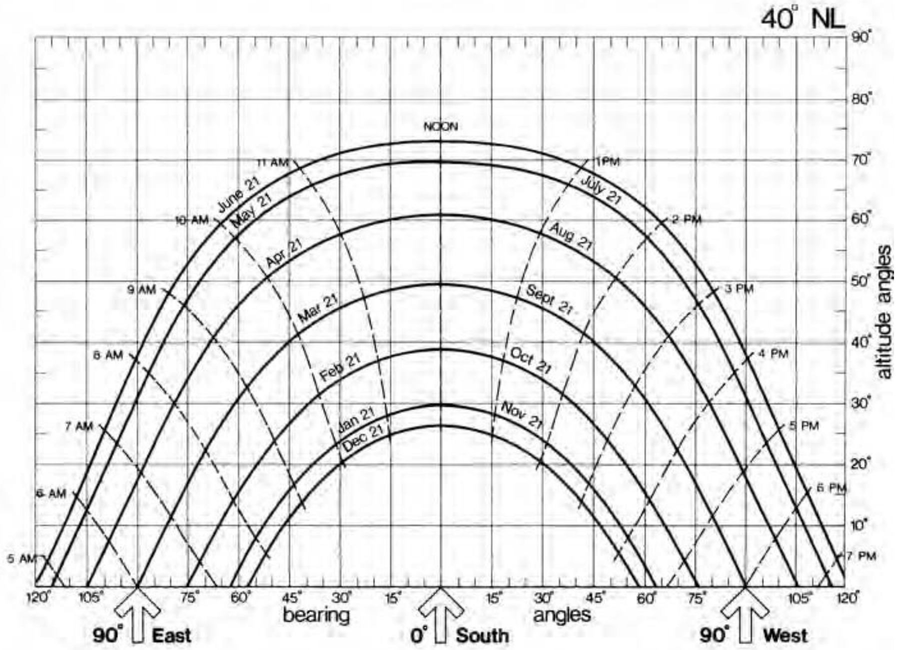


(b)

Fig. D.3 *(a–h) Set of vertical projection sunpath charts at 4° latitude intervals. Latitudes as indicated in the upper-right corner of each chart. (© Edward Mazria,* The Passive Solar Energy Book; *1979 used with permission.)*

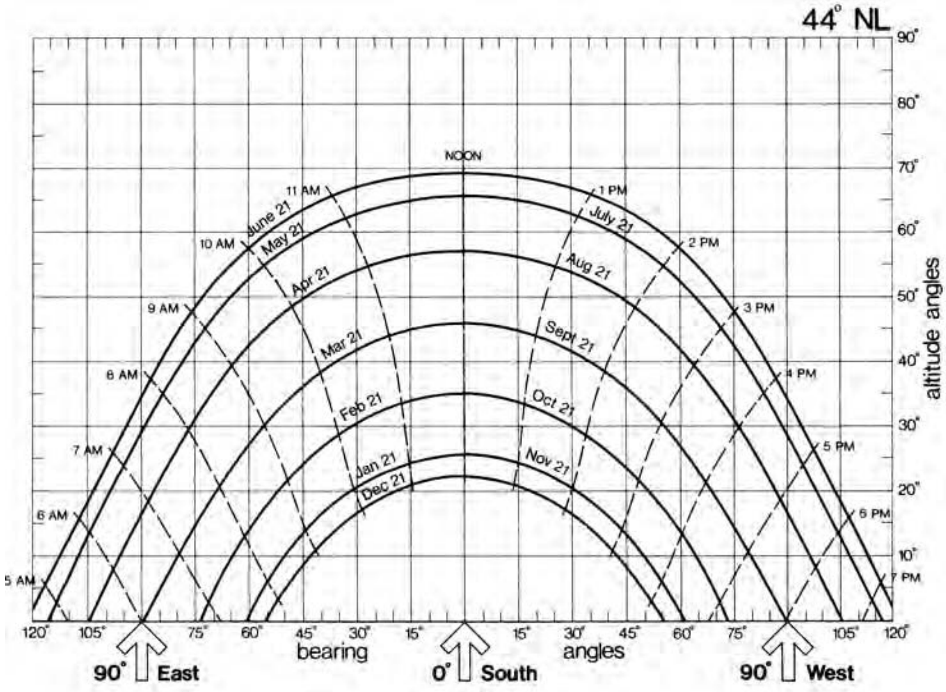


(c)

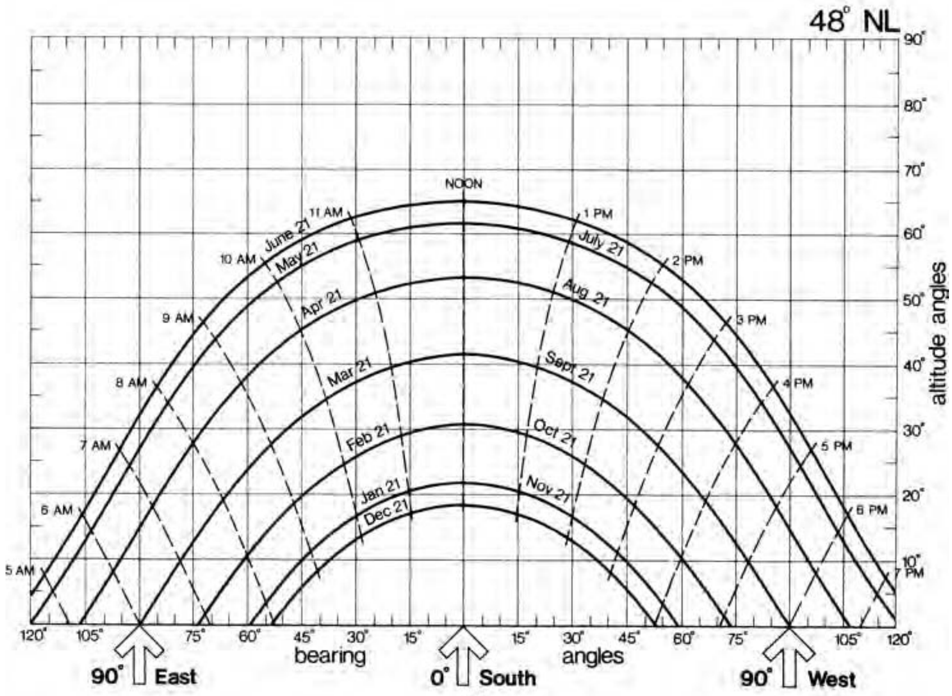


(d)

Fig. D.3 *(continued)*

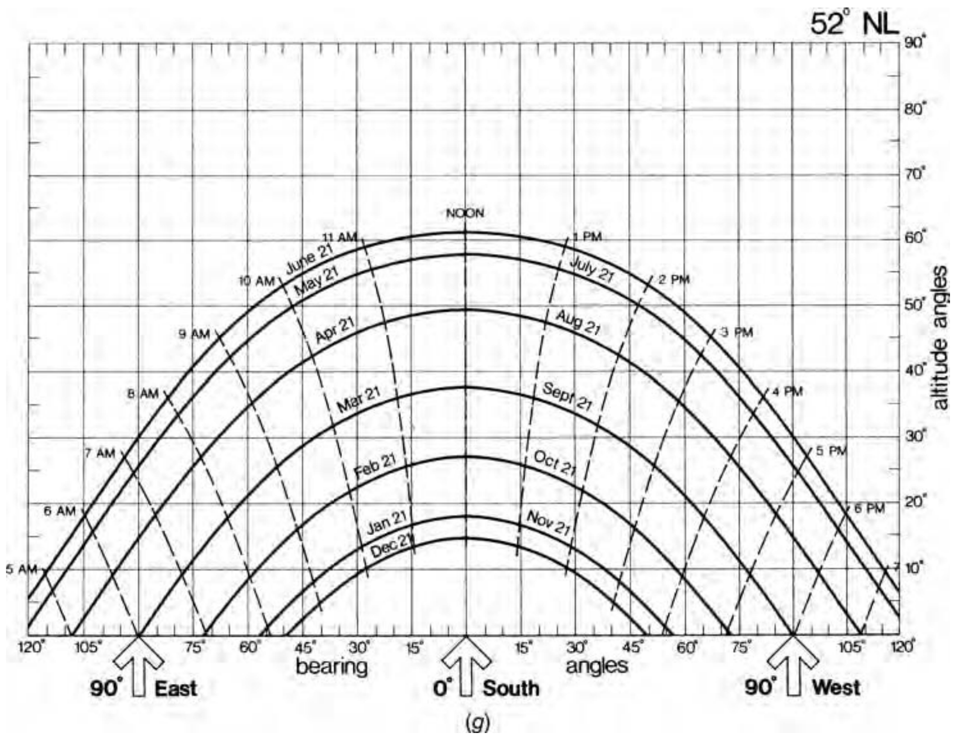


(e)

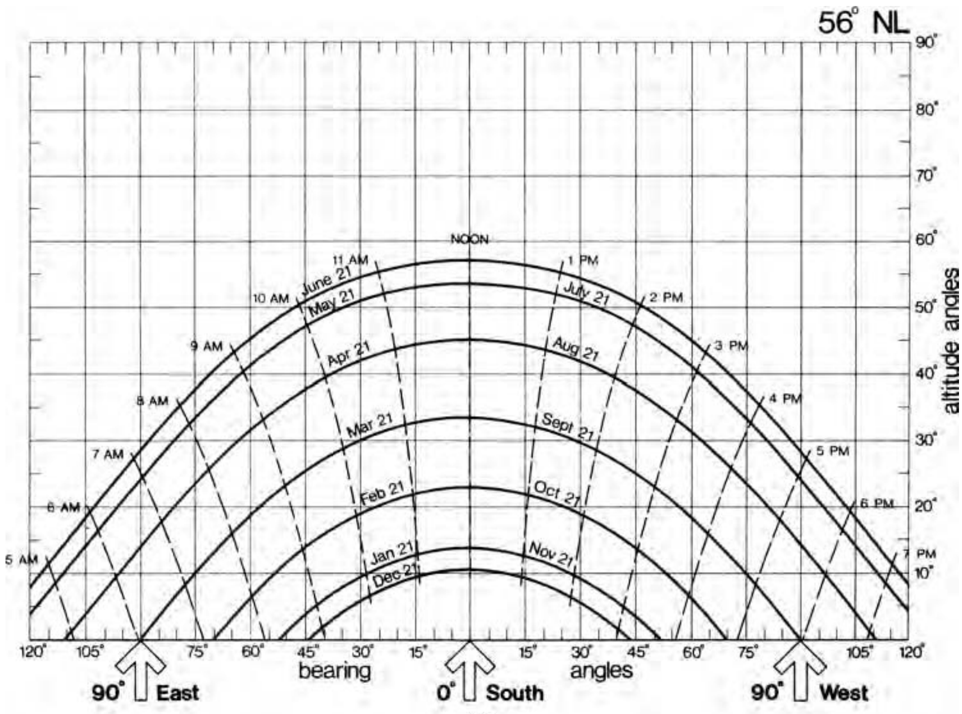


(f)

Fig. D.3 *(continued)*



(*g*)



(*h*)

Fig. D.3 *(continued)*

APPENDIX E

Thermal Properties of Materials and Assemblies

The tables in this appendix provide information on thermal (and occasionally visual) properties for a range of generic building materials and assemblies. The information provided herein would typically be used early in the design process before specific products have been selected and/or to determine the properties of assemblies that are fabricated from generic materials (such as gypsum wallboard, bricks, and concrete masonry units). When specific products (such as insulations, windows, or skylights) have been selected for use, data for those specific materials and assemblies should be obtained from appropriate manufacturers' resources (catalogs or websites) rather than from these tables.

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a]

Part A: I-P Units							
					I-P Resistance[c] (R)		
Description		Density lb/ft^3	Conductivity[b] (k) Btu-in /h ft^2 °F	Conductance (C) Btu/h ft^2 °F	Per Inch Thickness (1/k) °F ft^2 h/Btu-in.	For Thickness Listed (1/C) °F ft^2 h/Btu	Specific Heat Btu/lb °F
Building Board							
Asbestos–cement board		120	4.0	—	0.25	—	0.24
Asbestos–cement board	0.125 in.	120	—	33.00	—	0.03	—
Asbestos–cement board	0.25 in.	120	—	16.50	—	0.06	—
Gypsum or plaster board	0.375 in.	50	—	3.10	—	0.32	0.26
Gypsum or plaster board	0.5 in.	50	—	2.22	—	0.45	—
Gypsum or plaster board	0.625 in.	50	—	1.78	—	0.56	
Plywood (Douglas fir)[d]		34	0.80	—	1.25	—	0.29
Plywood (Douglas fir)	0.25 in.	34	—	3.20	—	0.31	—
Plywood (Douglas fir)	0.375 in.	34	—	2.13	—	0.47	—
Plywood (Douglas fir)	0.5 in.	34	—	1.60	—	0.62	—
Plywood (Douglas fir)	0.625 in.	34	—	1.29	—	0.77	—
Plywood or wood panels	0.75 in.	34	—	1.07	—	0.93	0.29
Vegetable fiber board							
Sheathing, regular density[e]	0.5 in.	18	—	0.76	—	1.32	0.31
	0.78125 in.	18	—	0.49	—	2.06	—
Sheathing intermediate density[e]	0.5 in.	22	—	0.92	—	1.09	0.31
Nail-base sheathing[e]	0.5 in.	25	—	0.94	—	1.06	0.31
Shingle backer	0.375 in.	18	—	1.06	—	0.94	0.31
Shingle backer	0.3125 in.	18	—	1.28	—	0.78	—
Sound-deadening board	0.5 in.	15	—	0.74	—	1.35	0.30
Tile and lay-in panels, plain or acoustic		18	0.40	—	2.50	—	0.14
	0.5 in.	18	—	0.80	—	1.25	—
	0.75 in.	18	—	0.53	—	1.89	—
Laminated paperboard		30	0.50	—	2.00	—	0.33
Homogeneous board from repulped paper		30	0.50	—	2.00	—	0.28
Hardboard[e]							
Medium density		50	0.73	—	1.37	—	0.31
High-density, service-tempered grade and service grade		55	0.82	—	1.22	—	0.32
High-density, standard-tempered grade		63	1.00	—	1.00	—	0.32
Particle board[e]							
Low density		37	0.71	—	1.41	—	0.31
Medium density		50	0.94	—	1.06	—	0.31
High density		62	0.5	1.18	—	0.85	—
Underlayment	0.625 in.	40	—	1.22	—	0.82	0.29
Waferboard		37	0.63	—	1.59	—	—
Wood subfloor	0.75 in.	—	6.0	1.06	—	0.94	0.33

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part A: I-P Units							
					I-P Resistance[c] (R)		
Description		**Density lb/ft³**	**Conductivity[b] (k) Btu-in /h ft² °F**	**Conductance (C) Btu/h ft² °F**	**Per Inch Thickness (1/k) °F ft² h/Btu-in.**	**For Thickness Listed (1/C) °F ft² h/Btu**	**Specific Heat Btu/lb °F**
Building Membrane							
Vapor—permeable felt		—	16.70	—	0.06	—	—
Vapor—seal, 2 layers of mopped 15-lb felt		—	8.35	—	0.12	—	—
Vapor—seal, plastic film		—	—	—	Negl.	—	—
Finish Flooring Materials							
Carpet and fibrous pad		—	0.48	—	2.08	0.34	—
Carpet and rubber pad		—	0.81	—	1.23	0.33	—
Cork tile	0.125 in.	—	—	3.60	—	0.28	0.48
Terrazzo	1 in.	—	—	12.50	—	0.08	0.19
Tile—asphalt, linoleum, vinyl, rubber		—	—	20.00	—	0.05	0.30
Vinyl asbestos		—	—	—	—	—	0.24
Ceramic							0.19
Wood, hardwood finish	0.75 in.	—	—	1.47	—	0.68	—
Insulating Materials							
Blanket and Batt[f,g]							
Mineral fiber, fibrous form processed from rock, slag, or glass							
Approx. 3–4 in.		0.4–2.0	—	0.091	—	11	—
Approx. 3.5 in.		0.4–2.0	—	0.077	—	13	—
Approx. 3.5 in.		1.2–1.6	—	0.067	—	15	—
Approx. 5.5–6.5 in.		0.4–2.0	—	0.053	—	19	—
Approx. 5.5 in.		0.6–1.0	—	0.048	—	21	—
Approx. 6–7.5 in.		0.4–2.0	—	0.045	—	22	—
Approx. 8.25–10 in.		0.4–2.0	—	0.033	—	30	—
Approx. 10–13 in.		0.4–2.0	—	0.026	—	38	—
Board and Slabs							
Cellular glass		8.0	0.33	—	3.03	—	0.18
Glass fiber, organic bonded		4.0–9.0	0.25	—	4.00	—	0.23
Expanded perlite, organic bonded		1.0	0.36	—	2.78	—	0.30
Expanded rubber (rigid)		4.5	0.22	—	4.55	—	0.40
Expanded polystyrene, extruded (smooth skin surface) (CFC-12 exp.)		1.8–3.5	0.20	—	5.00	—	0.29
Expanded polystyrene, extruded (smooth skin surface) (HCFC-142b exp)[h]		1.8–3.5	0.20	—	5.00	—	0.29
Expanded polystyrene, molded beads		1.0	0.26	—	3.85	—	—
Expanded polystyrene, molded beads		1.25	0.25	—	4.00	—	—
		1.5	0.24	—	4.17	—	—
		1.75	0.24	—	4.17	—	—
		2.0	0.23	—	4.35	—	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part A: I-P Units							
					I-P Resistance[c] (R)		
Description		**Density lb/ft^3**	**Conductivity[b] (k) Btu-in /h ft^2 °F**	**Conductance (C) Btu/h ft^2 °F**	**Per Inch Thickness (1/k) °F ft^2 h/Btu-in.**	**For Thickness Listed (1/C) °F ft^2 h/Btu**	**Specific Heat Btu/lb °F**
Cellular polyurethane/ polyisocyanurate[i] (CFC-11 exp.) (unfaced)		1.5	0.16–0.18	—	6.25–5.56	—	0.38
Cellular polyisocyanurate[i] (CFC-11 exp.) (gas-permeable facers)		1.5–2.5	0.16–0.18	—	6.25–5.56	—	0.22
Cellular polyisocyanurate[i] (CFC-11 exp.) (gas-impermeable facers)		2.0	0.14	—	7.04	—	0.22
Cellular phenolic (closed cell) (CFC-11, CFC-113 exp)[k]		3.0	0.12	—	8.20	—	—
Cellular phenolic (open cell)		1.8–2.2	0.23	—	4.40	—	—
Mineral fiber with resin binder		15.0	0.29	—	3.45	—	0.17
Mineral fiber board, wet felted							
Core or roof insulation		16–17	0.34	—	2.94	—	—
Acoustical tile		18.0	0.35	—	2.86	—	0.19
Acoustical tile		21.0	0.37	—	2.70	—	—
Mineral fiber board, wet molded							
Acoustical tile[1]		23.0	0.42	—	2.38	—	0.14
Wood or cane fiber board							
Acoustical tile[1]	0.5 in.	—	—	0.80	—	1.25	0.31
Acoustical tile[1]	0.75 in.	—	—	0.53	—	1.89	—
Interior finish (plank, tile)		15.0	0.35	—	2.86	—	0.32
Cement fiber slabs (shredded wood with Portland cement binder)		25–27.0	0.50–0.53	—	2.0–1.89	—	—
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)		22.0	0.57	—	1.75	—	0.31
Loose Fill							
Cellulosic insulation (milled paper or wood pulp)		2.3–3.2	0.27–0.32	—	3.70–3.13	—	0.33
Perlite, expanded		2.0–4.1	0.27–0.31	—	3.7–3.3	—	0.26
		4.1–7.4	0.31–0.36	—	3.3–2.8	—	—
		7.4–11.0	0.36–0.42	—	2.8–2.4	—	—
Mineral fiber (rock, slag, or glass)[g]							
Approx. 3.75–5 in.		0.6–2.0	—	—	—	11.0	0.17
Mineral fiber (rock, slag, or glass)[g]							
Approx. 6.5–8.75 in.		0.6–2.0	—	—	—	19.0	—
Approx. 7.5–10 in.		0.6–2.0	—	—	—	22.0	—
Approx. 10.3–13.7 in.		0.6–2.0	—	—	—	30.0	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part A: I-P Units							
					I-P Resistance[c] (R)		
Description		**Density lb/ft³**	**Conductivity[b] (k) Btu-in /h ft² °F**	**Conductance (C) Btu/h ft² °F**	**Per Inch Thickness (1/k) °F ft² h/Btu-in.**	**For Thickness Listed (1/C) °F ft² h/Btu**	**Specific Heat Btu/lb °F**
Mineral fiber (rock, slag, or glass)[g]		2.0–3.5	—	—	—	12.0–14.0	—
Vermiculite, exfoliated		7.0–8.2	0.47	—	2.13	—	0.32
		4.0–6.0	0.44	—	2.27	—	—
Spray Applied							
Polyurethane foam		1.5–2.5	0.16–0.18	—	6.25–5.56	—	—
Ureaformaldehyde foam		0.7–1.6	0.22–0.28	—	4.55–3.57	—	—
Cellulosic fiber		3.5–6.0	0.29–0.34	—	3.45–2.94	—	—
Glass fiber		3.5–4.5	0.26–0.27	—	3.85–3.70	—	—
Reflective Insulation							
Reflective material (ε < 0.5) in. center of ¾-in. cavity forms two ⅛-in. vertical air spaces[m]		—	—	0.31	—	3.2	—
Metals							
(See *2013 ASHRAE Handbook—Fundamentals*)							
Roofing							
Asbestos–cement shingles		120	—	4.76	—	0.21	0.24
Asphalt roll roofing		70	—	6.50	—	0.15	0.36
Asphalt shingles		70	—	2.27	—	0.44	0.30
Built-up roofing	0.375 in.	70	—	3.00	—	0.33	0.35
Slate	0.5 in.	—	—	20.00	—	0.05	0.30
Wood shingles, plain and plastic film faced		—	—	1.06	—	0.94	0.31
Plastering Materials							
Cement plaster, sand aggregate		116	5.0	—	0.20	—	0.20
Sand aggregate	0.375 in.	—	—	13.3	—	0.08	0.20
Sand aggregate	0.75 in.	—	—	6.66	—	0.15	0.20
Gypsum plaster							
Lightweight aggregate	0.5 in.	45	—	3.12	—	0.32	—
Lightweight aggregate	0.625 in.	45	—	2.67	—	0.39	—
Lightweight aggregate on metal lath	0.75 in.	—		2.13	—	0.47	—
Perlite aggregate		45	1.5	—	0.67	—	0.32
Sand aggregate		105	5.6	—	0.18	—	0.20
Sand aggregate	0.5 in.	105	—	11.10	—	0.09	—
Sand aggregate	0.625 in.	105	—	9.10	—	0.11	—
Sand aggregate on metal lath	0.75 in.	—	—	7.70	—	0.13	—
Vermiculite aggregate		45	1.7	—	0.59	—	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part A: I-P Units							
					I-P Resistance[c] (R)		
Description		**Density lb/ft³**	**Conductivity[b] (k) Btu-in /h ft² °F**	**Conductance (C) Btu/h ft² °F**	**Per Inch Thickness (1/k) °F ft² h/Btu-in.**	**For Thickness Listed (1/C) °F ft² h/Btu**	**Specific Heat Btu/lb °F**
Masonry Materials							
Masonry Units							
Brick, fired clay		150	8.4–10.2	—	0.12–0.10	—	—
		140	7.4–9.0	—	0.14–0.11	—	—
		130	6.4–7.8	—	0.16–0.12	—	—
		120	5.6–6.8	—	0.18–0.15	—	0.19
		110	4.9–5.9	—	0.20–0.17	—	—
		100	4.2–5.1	—	0.24–0.20	—	—
		90	3.6–4.3	—	0.28–0.24	—	—
		80	3.0–3.7	—	0.33–0.27	—	—
		70	2.5–3.1	—	0.40–0.33	—	—
Clay tile, hollow							
1 cell deep	3 in.	—	—	1.25	—	0.80	0.21
1 cell deep	4 in.	—	—	0.90	—	1.11	—
2 cells deep	6 in.	—	—	0.66	—	1.52	—
2 cells deep	8 in.	—	—	0.54	—	1.85	—
2 cells deep	10 in.	—	—	0.45	—	2.22	—
3 cells deep	12 in.	—	—	0.40	—	2.50	—
Concrete blocks[n,o]							
Limestone aggregate							
8 in., 36 lb, 138 lb/ft³ concrete, 2 cores with perlite-filled cores		—	—	0.48	—	2.1	—
Limestone aggregate							
12 in., 55 lb, 138 lb/ft³ concrete, 2 cores with perlite-filled cores		—	—	0.27	—	3.7	—
Normal weight aggregate (sand and gravel)							
8 in., 33–36 lb, 126–136 lb/ft³		—	—	0.90–1.03	—	1.11–0.97	0.22
Same with perlite-filled cores		—	—	0.50	—	2.0	—
Same with vermiculite-filled cores		—	—	0.52–0.73	—	1.92–1.37	—
12 in., 50 lb, 125 lb/ft³ concrete, 2 cores		—	—	0.81	—	1.23	0.22
Medium-weight aggregate (combinations of normal-weight and lightweight aggregate)							
8 in., 26–29 lb, 97–112 lb/ft³		—	—	0.58–0.78	—	1.71–1.28	—
Same with perlite-filled cores		—	—	0.27–0.44	—	3.7–2.3	—
Same with vermiculite-filled cores		—	—	0.30	—	3.3	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part A: I-P Units						
				I-P Resistance[c] (R)		
Description	**Density lb/ft³**	**Conductivity[b] (k) Btu-in /h ft² °F**	**Conductance (C) Btu/h ft² °F**	**Per Inch Thickness (1/k) °F ft² h/Btu-in.**	**For Thickness Listed (1/C) °F ft² h/Btu**	**Specific Heat Btu/lb °F**
Same with molded EPS (beads) filled cores	—	—	0.32	—	3.2	—
Same with molded EPS inserts in cores	—	—	0.37	—	2.7	—
Lightweight aggregate (expanded shale, clay, slate or slag, pumice)						
6 in., 16–17 lb, 85–87 lb/ft³	—	—	0.52–0.61	—	1.93–1.65	—
Same with perlite-filled cores	—	—	0.24	—	4.2	—
Same with vermiculite-filled cores	—	—	0.33	—	3.0	—
8 in., 19–22 lb, 72–86 lb/ft³	—	—	0.32–0.54	—	3.2–1.90	0.21
Same with perlite-filled cores	—	—	0.15–0.23	—	6.8–4.4	—
Same with vermiculite-filled cores	—	—	0.19–0.26	—	5.3–3.9	—
Same with molded EPS	—	—	0.21	—	4.8	—
Same with UF foam-filled cores	—	—	0.22	—	4.5	—
Same with molded EPS inserts in cores	—	—	0.29	—	3.5	—
12 in., 32–36 lb, 80–90 lb/ft³ concrete, 2 or 3 cores	—	—	0.38–0.44	—	2.6–2.3	—
Same with perlite-filled cores	—	—	0.11–0.16	—	9.2–6.3	—
Lightweight aggregate (expanded shale, clay, slate or slag, pumice)						
Same with vermiculite-filled cores	—	—	0.17	—	5.8	—
Stone, lime, or sand	180	72	—	0.01	—	—
Quartzitic and sandstone	160	43	—	0.02	—	—
	140	24	—	0.04	—	—
	120	13	—	0.08	—	0.19
Calcitic, dolomitic, limestone, marble, and granite	180	30	—	0.03	—	—
	160	22	—	0.05	—	—
	140	16	—	0.06	—	—
	120	11	—	0.09	—	0.19
	100	8	—	0.13	—	—
Gypsum partition tile						
3 × 12 × 30 in., solid	—	—	0.79	—	1.26	0.19
3 × 12 × 30 in., 4 cells	—	—	0.74	—	1.35	—
4 × 12 × 30 in., 3 cells	—	—	0.60	—	1.67	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part A: I-P Units						
				I-P Resistance[c] (R)		
Description	Density lb/ft^3	Conductivity[b] (k) Btu-in /h ft^2 °F	Conductance (C) Btu/h ft^2 °F	Per Inch Thickness (1/k) °F ft^2 h/Btu-in.	For Thickness Listed (1/C) °F ft^2 h/Btu	Specific Heat Btu/lb °F
Concretes[o]						
Sand and gravel or stone aggregate concretes	150	10.0–20.0	—	0.10–0.05	—	—
(Concretes with more than 50% quartz or quartzite sand have conductivities in the higher end of the range)	140	9.0–18.0	—	0.11–0.06	—	0.19-0.24
	130	7.0–13.0	—	0.14–0.08	—	—
Limestone concretes	140	11.1	—	0.09	—	—
	120	7.9	—	0.13	—	—
	100	5.5	—	0.18	—	—
Gypsum-fiber concrete (87.5% gypsum, 12.5% wood chips)	51	1.66	—	0.60	—	0.21
Cement/lime, mortar, and stucco	120	9.7	—	0.10	—	—
	100	6.7	—	0.15	—	—
	80	4.5	—	0.22	—	—
Lightweight aggregate concretes						
Expanded shale, clay, or slate; expanded slags; cinders; pumice with density up to 100 lb/ft^3); and scoria (sanded concretes have conductivities in the higher end of the range)	120	6.4–9.1	—	0.16–0.11	—	—
	100	4.7–6.2	—	0.21–0.16	—	0.20
	80	3.3–4.1	—	0.30–0.24	—	0.20
	60	2.1–2.5	—	0.48–0.40	—	—
	40	1.3	—	0.78	—	—
Perlite, vermiculite, and polystyrene beads	50	1.8–1.9	—	0.55–0.53	—	—
	40	1.4–1.5	—	0.71–0.67	—	0.15–0.23
	30	1.1	—	0.91	—	—
	20	0.8	—	1.25	—	—
Foam concretes	120	5.4	—	0.19	—	—
	100	4.1	—	0.24	—	—
	80	3.0	—	0.33	—	—
	70	2.5	—	0.40	—	—
Foam concretes and cellular concretes	60	2.1	—	0.48	—	—
	40	1.4	—	0.71	—	—
	20	0.8	—	1.25	—	—
Siding Materials (on flat surface)						
Shingles						
Asbestos–cement	120	—	4.75	—	0.21	—
Wood, 16 in., 7.5-in. exposure	—	—	1.15	—	0.87	0.31
Wood, double, 16-in., 12-in. exposure	—	—	0.84	—	1.19	0.28
Wood, plus ins. backer board, 0.312 in.	—	—	0.71	—	1.40	0.31

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part A: I-P Units						
				I-P Resistance[c] (R)		
Description	**Density lb/ft³**	**Conductivity[b] (k) Btu-in /h ft² °F**	**Conductance (C) Btu/h ft² °F**	**Per Inch Thickness (1/k) °F ft² h/Btu-in.**	**For Thickness Listed (1/C) °F ft² h/Btu**	**Specific Heat Btu/lb °F**
Siding						
Asbestos–cement, 0.25 in. lapped	—	—	4.76	—	0.21	0.24
Asphalt roll siding	—	—	6.50	—	0.15	0.35
Asphalt insulating siding (0.5 in. bed.)	—	—	0.69	—	1.46	0.35
Hardboard siding, 0.4375 in.	—	—	1.49	—	0.67	0.28
Wood, drop, 1 × 8 in.	—	—	1.27	—	0.79	0.28
Wood, bevel, 0.5 × 8 in., lapped	—	—	1.23	—	0.81	0.28
Wood, bevel, 0.75 × 10 in., lapped	—	—	0.95	—	1.05	0.28
Wood, plywood, 0.375 in. lapped	—	—	1.69	—	0.59	0.29
Aluminum, steel, or vinyl[p,q] over sheathing						
Hollow-backed	—	—	1.64	—	0.61	0.29[q,l]
Insulating-board backed nominal 0.375 in.	—	—	0.55	—	1.82	0.32
Insulating-board backed nominal 0.375 in, foil-backed	—	—	0.34	—	2.96	—
Architectural (soda-lime float) glass	158	6.9	—	—	—	0.21
Woods (12% moisture content)[e,r]						
Hardwoods						0.39[s]
Oak	41.2–46.8	1.12–1.25	—	0.89–0.80	—	—
Birch	42.6–45.4	1.16–1.22	—	0.87–0.82	—	—
Maple	39.8–44.0	1.09–1.19	—	0.92–0.84	—	—
Ash	38.4–41.9	1.06–1.14	—	0.94–0.88	—	—
Softwoods						0.39[s]
Southern pine	35.6–441.2	1.00–1.12	—	1.00–0.89	—	—
Douglas fir-larch	33.5–36.3	0.95–1.01	—	1.06–0.99	—	—
Southern cypress	31.4–32.1	0.90–0.92	—	1.11–1.09	—	—
Hem-fir, spruce-pine-fir	24.5–31.4	0.74–0.90	—	1.35–1.11	—	—
West Coast woods, cedars	21.7–31.4	0.68–0.90	—	1.48–1.11	—	—
California redwood	24.5–28.0	0.74–0.82	—	1.35–1.22	—	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units							
					SI Resistance[c] (R)		
Description		**Density kg/m^3**	**Conductivity[b] (k) W/m K**	**Conductance (C) W/m^2 K**	**Per Meter Thickness (1/k) K m/W**	**For Thickness Listed (1/C) K m^2/W**	**Specific Heat kJ/kg K**
Building Board							
Asbestos–cement board		1900	0.58	—	1.73	—	1.00
Asbestos–cement board	3.2 mm	1900	—	187.4	—	0.005	—
Asbestos–cement board	6.4 mm	1900	—	93.7	—	0.011	—
Gypsum or plaster board	9.5 mm	800	—	17.6	—	0.056	1.09
Gypsum or plaster board	12.7 mm	800	—	12.6	—	0.079	—
Gypsum or plaster board	15.9 mm	800	—	10.1	—	0.099	—
Plywood (Douglas fir)[d]		540	0.12	—	8.66	—	1.21
Plywood (Douglas fir)	6.4 mm	540	—	18.2	—	0.055	—
Plywood (Douglas fir)	9.5 mm	540	—	12.1	—	0.083	—
Plywood (Douglas fir)	12.7 mm	540	—	9.1	—	0.11	—
Plywood (Douglas fir)	15.9 mm	540	—	7.3	—	0.14	—
Plywood or wood panels	19.0 mm	540	—	6.1	—	0.16	1.21
Vegetable fiber board							
Sheathing, regular density[e]	12.7 mm	290	—	4.3	—	0.23	1.3
	19.8 mm	290	—	2.8	—	0.36	—
Sheathing intermediate density[e]	12.7 mm	350	—	5.2	—	0.19	1.30
Nail-base sheathing[e]	12.7 mm	400	—	5.3	—	0.19	1.30
Shingle backer	9.5 mm	290	—	6.0	—	0.17	1.30
Shingle backer	7.9 mm	290	—	7.3	—	0.14	—
Sound-deadening board	12.7 mm	240	—	4.2	—	0.24	1.26
Tile and lay-in panels, plain or acoustic		290	0.058	—	17.0	—	0.59
	12.7 mm	290	—	4.5	—	0.22	—
	19.0 mm	290	—	3.0	—	0.33	—
Laminated paperboard		480	0.072	—	—	—	1.38
Homogeneous board from repulped paper		480	0.072	—		—	1.17
Hardboard[e]							
Medium density		800	0.105	—	9.50	—	1.30
High-density, service-tempered grade and service grade		880	0.118	—	8.46	—	1.34
High-density, standard-tempered grade		1010	0.144	—	6.93	—	1.34
Particle board[e]							
Low density		590	0.102	—	9.77	—	1.30
Medium density		800	0.135	—	7.35	—	1.30
High density		1000	0.17	—	5.90	—	1.30
Underlayment	15.9 mm	640	—	6.9	—	0.14	1.21
Waferboard		37	0.63	—	11.0	—	—
Wood subfloor	19.0 mm	—	—	6.0	—	0.17	1.38

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units							
					SI Resistance[c] (R)		
Description		**Density kg/m³**	**Conductivity[b] (k) W/m K**	**Conductance (C) W/m² K**	**Per Meter Thickness (1/k) K m/W**	**For Thickness Listed (1/C) K m²/W**	**Specific Heat kJ/kg K**
Building Membrane							
Vapor—permeable felt	—	—	94.9	—	0.011	—	—
Vapor—seal, 2 layers of mopped 0.73-kg/m² felt	—	—	47.4		0.21	—	—
Vapor—seal, plastic film	—	—	—	—	Negl.	—	—
Finish Flooring Materials							
Carpet and fibrous pad	—	—	2.73	—	0.37	—	1.42
Carpet and rubber pad	—	—	4.60	—	0.22	—	1.38
Cork tile	3.2 mm	—	—	20.4		0.049	2.01
Terrazzo	25.0 mm	—	—	71.0	—	0.014	0.80
Tile—asphalt, linoleum, vinyl, rubber		—	—	113.6	—	0.009	1.26
Vinyl asbestos		—	—	—	—	—	1.01
Ceramic		—	—	—	—	—	0.80
Wood, hardwood finish	19 mm		8.35	—	—	0.12	—
Insulating Materials							
Blanket and Batt[f,g]							
Mineral fiber, fibrous form processed from rock, slag, or glass							
75–100 mm		6.4–32.0	—	0.52	—	1.94	—
90 mm		6.4–32.0	—	0.44	—	2.29	—
90 mm		19.0–26.0	—	0.38	—	2.63	—
140–165 mm		6.4–32.0	—	0.30	—	3.32	—
140 mm		10.0–16.0	—	0.27	—	3.67	—
150–190 mm		6.4–32.0	—	0.26	—	3.91	—
210–250 mm		6.4–32.0	—	0.19	—	5.34	—
250–330 mm		6.4–32.0	—	0.15	—	6.77	—
Board and Slabs							
Cellular glass		136	0.050	—	19.8	—	0.75
Glass fiber, organic bonded		64–140	0.036	—	27.7	—	0.96
Expanded perlite, organic bonded		16	0.052	—	19.3	—	1.26
Expanded rubber (rigid)		72	0.032	—	31.6	—	1.68
Expanded polystyrene, extruded (smooth skin surface) (CFC-12 exp.)		29–56	0.029	—	34.7	—	1.21
Expanded polystyrene, extruded (smooth skin surface) (HCFC-142b exp)[h]		29–56	0.029	—	34.7	—	1.21
Expanded polystyrene, molded beads		16	0.037	—	26.7	—	—
		20	0.036	—	27.7	—	—
		24	0.035	—	28.9	—	—
		28	0.035	—	28.9	—	—
		32	0.033	—	30.2	—	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units							
					SI Resistance[c] (R)		
Description		**Density kg/m³**	**Conductivity[b] (k) W/m K**	**Conductance (C) W/m² K**	**Per Meter Thickness (1/k) K m/W**	**For Thickness Listed (1/C) K m²/W**	**Specific Heat kJ/ kg K**
Cellular polyurethane/ polyisocyanurate[i] (CFC-11 exp.) (unfaced)		24	0.023–0.026	—	43.3–38.5	—	1.59
Cellular polyisocyanurate[i] (CFC-11 exp.) (gas-permeable facers)		24–40	0.023–0.026	—	43.3–38.5	—	0.92
Cellular polyisocyanurate[i] (CFC-11 exp.) (gas-impermeable facers)		32	0.020	—	48.8	—	0.92
Cellular phenolic (closed cell) (CFC-11, CFC-113 exp.)[k]		32	0.017	—	56.8	—	—
Cellular phenolic (open cell)		29–35	0.033	—	30.5	—	—
Mineral fiber with resin binder		240	0.042	—	23.9	—	—
Mineral fiber board, wet felted							
Core or roof insulation		260–270	0.049	—	20.4	—	—
Acoustical tile		290	0.050	—	19.8	—	0.80
Acoustical tile		340	0.053	—	18.7	—	—
Mineral fiber board, wet molded							
Acoustical tile[1]		370	0.060	—	16.5	—	0.59
Wood or cane fiber board							
Acoustical tile[1]	12.7 mm	—	—	4.5	—	0.22	1.30
Acoustical tile[1]	19 mm	—	—	3.0	—	0.33	—
Interior finish (plank, tile)		240	0.050	—	19.8	—	1.34
Cement fiber slabs (shredded wood with Portland cement binder)		400–430	0.072–0.076	—		—	—
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)		350	0.082	—	12.1	—	1.30
Loose Fill							
Cellulosic insulation (milled paper or wood pulp)		37–51	0.039–0.046	—	25.6–21.7	—	1.38
Perlite, expanded		32–66	0.039–0.045	—	25.6–22.9	—	1.09
		66–120	0.045–0.052	—	22.9–19.4	—	—
		120–180	0.052–0.060	—	19.4–16.6	—	—
Mineral fiber (rock, slag, or glass)[g]							
95–130 mm		9.6–32	—	—	—	1.94	0.71
170–220 mm		9.6–32	—	—	—	3.35	—
190–250 mm		9.6–32	—	—	—	3.87	—
260–350 mm		9.6–32	—	—	—	5.28	—
Approx. 90 mm (closed sidewall application)		32–56	—	—	—	2.1–2.5	—
Vermiculite, exfoliated		110–130	0.068	—	14.8	—	1.34
		64–96	0.063	—	15.7	—	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units							
					SI Resistance[c] (R)		
Description		**Density kg/m^3**	**Conductivity[b] (k) W/m K**	**Conductance (C) W/m^2 K**	**Per Meter Thickness (1/k) K m/W**	**For Thickness Listed (1/C) K m^2/W**	**Specific Heat kJ/kg K**
Spray Applied							
Polyurethane foam		24–40	0.023–0.026	—	43.3–38.5	—	—
Ureaformaldehyde foam		11–26	0.032–0.040	—	31.5–24.7	—	—
Cellulosic fiber		56–96	0.042–0.049	—	23.9–20.4	—	—
Glass fiber		56–72	0.038–0.039	—	26.7–25.6	—	—
Reflective Insulation							
Reflective material ($\varepsilon < 0.5$) in. center of 20-mm cavity forms two 10-mm vertical air spaces[m]		—	—	1.76	—	0.57	—
Metals							
(See 2013 *ASHRAE Handbook—Fundamentals*)							
Roofing							
Asbestos–cement shingles		1900	—	27.0	—	0.037	1.0
Asphalt roll roofing		1100	—	36.9	—	0.026	1.51
Asphalt shingles		1100	—	12.9	—	0.077	1.26
Built-up roofing	10 mm	1100	—	17.0	—	0.058	1.46
Slate	13 mm			114.0	—	0.009	1.26
Wood shingles, plain and plastic film faced		—	—	6.0	—	0.166	1.30
Plastering Materials							
Cement plaster, sand aggregate		1860	0.72	—	1.39	—	0.84
Sand aggregate	10 mm	—	—	75.5	—	0.013	0.84
Sand aggregate	20 mm	—	—	37.8	—	0.026	0.84
Gypsum plaster							
Lightweight aggregate	13 mm	720	—	17.7	—	0.056	—
Lightweight aggregate	16 mm	720	—	15.2	—	0.066	—
Lightweight aggregate on metal lath	19 mm	—	—	12.1	—	0.083	—
Perlite aggregate		720	0.22	—	4.64	—	1.34
Sand aggregate		1680	0.81	—	1.25	—	0.84
Sand aggregate	13 mm	1680	—	63.0	—	0.016	—
	16 mm	1680	—	51.7	—	0.019	—
Sand aggregate on metal lath	19 mm	—	—	43.7	—	0.023	—
Vermiculite aggregate		720	0.24	—	4.09	—	—
Masonry Materials							
Masonry Units							
Brick, fired clay		2400	1.21–1.47	—	0.83–0.68	—	—
		2240	1.07–1.30	—	0.94–0.77	—	—
		2080	0.92–1.12	—	1.08–0.89	—	—
		1920	0.81–0.98	—	1.24–1.02	—	0.79
		1760	0.71–0.85	—	1.42–1.18	—	—
		1600	0.71–0.85	—	1.65–1.36	—	—
		1440	0.52–0.62	—	1.93–1.61	—	—
		1280	0.43–0.53	—	2.31–1.87	—	—
		1120	0.36–0.45		2.77–2.23		

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units							
					SI Resistance[c] (R)		
Description		**Density kg/m³**	**Conductivity[b] (k) W/m K**	**Conductance (C) W/m² K**	**Per Meter Thickness (1/k) K m/W**	**For Thickness Listed (1/C) K m²/W**	**Specific Heat kJ/ kg K**
Clay tile, hollow							
1 cell deep	75 mm	—	—	7.10	—	0.14	0.88
1 cell deep	100 mm	—	—	5.11	—	0.20	—
2 cells deep	150 mm	—	—	3.75	—	0.27	—
2 cells deep	200 mm	—	—	3.07	—	0.33	—
2 cells deep	250 mm	—	—	2.56	—	0.39	—
3 cells deep	300 mm	—	—	2.27	—	0.44	—
Concrete blocks[n,o]							
Limestone aggregate							
200 mm, 16.3 kg, 2210 kg/m³ 2 cores with perlite-filled cores		—	—	2.73	—	0.37	—
Limestone aggregate							
300 mm, 25 kg, 2210 kg/m³ 2 cores with perlite-filled cores		—	—	1.53	—	0.65	—
Normal weight aggregate (sand and gravel)							
200 mm, 15–16 kg, 2020–2180 kg/m³ concrete, 2 or 3 cores		—	—	5.1–5.8	—	0.20–0.17	0.92
Same with perlite-filled cores		—	—	2.84	—	0.35	—
Same with vermiculite-filled cores		—	—	3.0–4.1	—	0.34–0.24	—
300 mm, 22.7 kg, 2000 kg/m³ 2 cores		—	—	4.60	—	0.217	0.92
Medium-weight aggregate (combinations of normal-weight and lightweight aggregate)							
200 mm, 15–16 kg, 2020–2180 kg/m³ concrete, 2 or 3 cores		—	—	3.3–4.4	—	0.30–0.22	—
Same with perlite-filled cores		—	—	1.5–2.5	—	0.65–0.41	—
Same with vermiculite-filled cores		—	—	1.70	—	0.58	—
Same with molded EPS (beads filled cores		—	—	1.82	—	0.56	—
Same with molded EPS inserts in cores		—	—	2.10	—	0.47	—
Lightweight aggregate (expanded shale, clay, slate or slag, pumice)							
150 mm, 7.3–7.7 kg, 1360–1390 kg/m³ concrete, 2 or 3 cores		—	—	3.0–3.5	—	0.34–0.29	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units						
				SI Resistance[c] (R)		
Description	Density kg/m^3	Conductivity[b] (k) W/m K	Conductance (C) W/m^2 K	Per Meter Thickness (1/k) K m/W	For Thickness Listed (1/C) K m^2/W	Specific Heat kJ/kg K
Same with perlite-filled cores	—	—	1.36	—	0.74	—
Same with vermiculite-filled cores	—	—	1.87	—	0.53	—
200 mm, 8.6–10 kg, 1150–1360 kg/m^3 concrete, 2 or 3 cores	—	—	1.8-3.1	—	0.56–0.33	0.88
Same with perlite-filled cores	—	—	0.9–1.3	—	1.20–0.77	—
Same with vermiculite-filled cores	—	—	1.1–1.5	—	0.93–0.69	—
Same with molded EPS	—	—	1.19	—	0.85	—
(beads) filled cores						
Same with UF foam-filled cores	—	—	1.25	—	0.79	—
Same with molded EPS inserts in cores	—	—	1.65	—	0.62	—
300 mm, 14.5–16.3 kg, 1280–1440 kg/m^3 2 or 3 cores	—	—	2.2–2.5	—	0.46–0.40	—
Same with perlite-filled cores	—	—	0.6–0.9	—	1.6–1.1	—
Same with vermiculite-filled cores	—	—	0.97	—	1.0	—
Stone, lime, or sand	2880	10.4	—	0.10	—	—
Quartzitic and sandstone	160	43	—		—	—
	2560	6.2	—	0.16	—	—
	2240	3.5	—	0.29	—	—
	1920	1.9	—	0.53	—	0.19
Calcitic, dolomitic, limestone, marble, and granite	2880	4.3	—	0.23	—	—
	2560	3.2	—	0.32	—	—
	2240	2.3	—	0.43	—	—
	1920	1.6	—	0.63	—	—
	1600	1.1	—	0.90	—	—
Gypsum partition tile						
(75 × 300 × 760 mm)		—	4.50	—	0.222	0.79
(75 × 300 × 760 mm)		—	4.20	—	0.238	—
(100 × 300 × 760 mm)		—	3.40	—	0.294	—
Concretes[o]						
Sand and gravel or stone aggregate concretes	2400	1.4–2.9	—	0.69–0.35	—	—
(Concretes with more than 50% quartz or quartzite sand have conductivities in the higher end of the range)	2240	1.3–2.6	—	0.77–0.39	—	0.8–1.0
	2080	1.0–1.9	—	0.99–0.53	—	—
Limestone concretes	2240	1.60	—	0.62	—	—
	1920	1.14	—	0.88	—	—
	1600	0.79	—	1.26	—	—

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units						
				SI Resistance[c] (R)		
Description	**Density kg/m³**	**Conductivity[b] (k) W/m K**	**Conductance (C) W/m² K**	**Per Meter Thickness (1/k) K m/W**	**For Thickness Listed (1/C) K m²/W**	**Specific Heat kJ/kg K**
Gypsum-fiber concrete (87.5% gypsum, 12.5% wood chips)	816	0.24	—	4.18	—	0.88
Cement/lime, mortar, and stucco	1920	1.40	—	0.71	—	—
	1600	0.97	—	1.04	—	—
	1280	0.65	—	1.54	—	—
Lightweight aggregate concretes						
Expanded shale, clay, or slate; expanded slags; cinders; pumice (with density up to 1600 kg/m³); and scoria (sanded concretes have conductivities in the higher end of the range)	1920	0.9–1.3	—	1.08–0.76	—	—
	1600	0.68–0.89	—	1.48–1.12	—	0.84
	1280	0.48–0.59	—	2.10–1.69	—	0.84
	960	0.30–0.36	—	3.30–2.77	—	—
	640	0.18	—	5.40	—	—
Perlite, vermiculite, and polystyrene beads	800	0.26–0.27	—	3.81–3.68	—	—
	640	0.20–0.22	—	4.92–4.65	—	0.63–0.96
	480	0.16	—	6.31	—	—
	320	0.12	—	8.67	—	—
Foam concretes	1920	0.75	—	1.32	—	—
	1600	0.60	—	1.66	—	—
	1280	0.44	—	2.29	—	—
	1120	0.36	—	2.77	—	—
Foam concretes and cellular concretes	960	0.30	—	3.33	—	—
	640	0.20	—	4.92	—	—
	320	0.12	—	8.67	—	—
Siding Materials (on flat surface)						
Shingles						
Asbestos–cement	1900	—	27.0	—	0.037	—
Wood, 400 mm, 190 mm exposure	—	—	6.53	—	0.15	1.30
Wood, double, 400 mm, 300 mm. exposure	—	—	4.77	—	0.21	1.17
Wood, plus ins. backer board, 8 mm	—	—	4.03	—	0.25	1.30
Siding						
Asbestos–cement, 6.4 mm lapped	—	—	27.0	—	0.037	1.01
Asphalt roll siding	—	—	36.9	—	0.026	1.47
Asphalt insulating siding (12.7 mm bed.)	—	—	3.92	—	0.26	1.47
Hardboard siding, 11 mm	—	—	8.46	—	0.12	1.17
Wood, drop, 25 × 200 mm	—	—	7.21	—	0.14	1.17
Wood, bevel, 13 × 200 mm, lapped	—	—	6.98	—	0.14	1.17

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units						
				SI Resistance[c] (R)		
Description	**Density kg/m^3**	**Conductivity[b] (k) W/m K**	**Conductance (C) W/m^2 K**	**Per Meter Thickness (1/k) K m/W**	**For Thickness Listed (1/C) K m^2/W**	**Specific Heat kJ/kg K**
Wood, bevel, 19 × 250 mm, lapped	—	—	5.40	—	0.18	1.17
Wood, plywood, 9.5 mm lapped	—	—	9.60	—	0.10	1.22
Aluminum, steel, or vinyl[p,q] over sheathing						
Hollow-backed	—	—	9.31	—	0.11	1.22
Insulating-board backed nominal 9.5 mm	—	—	3.12	—	0.32	1.34
Insulating-board backed nominal 9.5 mm, foil-backed	—	—	1.93	—	0.52	—
Architectural (soda-lime float) glass	2528	—	56.8	—	0.018	0.84
Woods (12% moisture content)[e,r]						
Hardwoods						1.63[s]
Oak	659–749	0.16–0.18		6.2–5.5	—	—
Birch	682–726	0.167–0.176		6.0–5.7	—	—
Maple	637–704	0.157–0.171		6.4–5.8	—	—
Ash	614–670	0.153–0.164		6.5–6.1	—	—
Softwoods						1.63[s]
Southern pine	570–659	0.144–0.161		6.9–6.2	—	—
Douglas fir-larch	536–581	0.13–0.145		7.3–6.9	—	—
Southern cypress	502–514	0.130–0.132		7.7–7.6	—	—
Hem-fir, spruce-pine-fir	392–502	0.107–0.130		9.3–7.7	—	—
West Coast woods, cedars	347–502	0.098–0.130		10.3–7.7	—	—
California redwood	392–448	0.107–0.118		9.4–8.5	—	—

Source: Previously adapted, with the permission of ASHRAE, from the *2001 ASHRAE Handbook—Fundamentals.* This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

Note: The SI units for various properties were appended to the ASHRAE I-P data by the authors.

[a]Values are for a mean temperature of 75ºF (24ºC). Representative values for dry materials are intended as design (not specification) values for materials in normal use. Thermal values of insulating materials may differ from design values depending on their in situ properties (e.g., density, moisture content, orientation) and variability experienced during manufacture. For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests.

[b]To obtain thermal conductivities in Btu/h ft ºF, divide the k-factor by 12 in./ft.

[c]Resistance values are the reciprocals of C before rounding off C to two decimal places.

[d]From Lewis (1967), *Thermal Conductivity of Wood-Base Fiber and Particle Panel Materials*. Forest Products Laboratory, Research Paper FPL 77, June.

[e]U.S. Dept. of Agriculture (1974), *Wood Handbook*, Handbook No. 72.

[f]Does not include paper backing and facing, if any. Where insulation forms a boundary (reflective or otherwise) of an air space, see Tables E.3 and E.4/E.5 for the insulating value of an air space with the appropriate effective emittance and temperature conditions of the space.

[g]Conductivity varies with fiber diameter. (See Chapter 23, "Factors Affecting Thermal Performance," of 2001 *ASHRAE Handbook—Fundamentals*.) Batt, blanket, and loose-fill mineral fiber insulations are manufactured to achieve specified R-values, the most common of which are listed in the table. Due to differences in manufacturing processes and materials, the product thicknesses, densities, and thermal conductivities vary over considerable ranges for a specified R-value.

[h]This material is relatively new, and data are based on limited testing.

TABLE E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

[i]For additional information, see Society of the Plastics Industry (SPI) Bulletin U108. Values are for aged, unfaced board stock. For change in conductivity with age of expanded polyurethane/polyisocyanurate, see Chapter 23, "Factors Affecting Thermal Performance," of 2001 *ASHRAE Handbook—Fundamentals*.

[j]Values are for aged products with gas-impermeable facers on the two major surfaces. An aluminum foil facer of 0.001 in. (25 μm) thickness or greater is generally considered impermeable to gases. For change in conductivity with age of expanded polyisocyanurate, see Chapter 23, "Factors Affecting Thermal Performance," of 2001 *ASHRAE Handbook—Fundamentals*.

[k]Cellular phenolic insulation may no longer be manufactured. These thermal conductivity and resistance values do not represent aged insulation, which may have higher thermal conductivity and lower thermal resistance.

[l]Insulating values of acoustical tile vary, depending on density of the board and on type, size, and depth of perforations.

[m]Cavity is framed with 0.75-in. (20-mm) wood furring strips. Caution should be used in applying this value for other framing materials. The reported value was derived from tests and applies to the reflective path only. The effect of studs or furring strips must be included in determining the overall performance of the wall.

[n]Values for fully grouted block may be approximated using values for concrete with a similar unit weight.

[o]Values for concrete block and concrete are at moisture contents representative of normal use.

[p]Values for metal or vinyl siding applied over flat surfaces vary widely, depending on amount of ventilation of air space beneath the siding; whether air space is reflective or nonreflective; and on thickness, type, and application of insulating backing used. Values are averages for use as design guides, and were obtained from several guarded hot box tests (ASTM C 236) or calibrated hot box (ASTM C 976) on hollow-backed types and types made using backing-boards of wood fiber, foamed plastic, and glass fiber. Departures of 650% or more from these values may occur.

[q]Vinyl specific heat = 0.25 Btu/lb ºF (1.0 kJ/kg K).

[r]See Adams (1971). "Supporting Cryogenic Equipment with Wood." *Chemical Engineering* (May): pp. 156–158); MacLean (1941). "Thermal Conductivity of Wood." *ASHVE Transactions* 47:323; and Wilkes (1979). "Thermophysical Properties Data Base Activities at Owens-Corning Fiberglas." *Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings*, ASHRAE SP 28:662–77. The conductivity values listed are for heat transfer across the grain. The thermal conductivity of wood varies linearly with the density, and the density ranges listed are those normally found for the wood species given. If the density of the wood species is not known, use the mean conductivity value. For extrapolation to other moisture contents, refer to the equation presented in footnote "r" on page 25.9 of the 2001 *ASHRAE Handbook—Fundamentals*.

[s]For an empirical equation for the specific heat of moist wood at 75ºF (24ºC), refer to the equation presented in footnote "s" on page 25.9 of the 2001 *ASHRAE Handbook—Fundamentals*.

TABLE E.2 Thermal Properties of Alternative[a] Building and Insulating Materials

Part A: I-P Units					
Description	**Density lb/ft^3**	**Conductivity (k) Btu-in/h ft^2 °F**	**Conductance (C) Btu/h ft^2 °F**	**Resistance Per Inch Thickness (1/k) h ft^2 °F/Btu-in.**	**Resistance for Thickness Listed h ft^2 °F/Btu**
Building Materials					
Adobe[b] typically 10–24 in.	1006	3.3	—	0.3	—
Cob[c] typically 18–36 in.	—	4	—	0.25	—
Rammed earth[d] 18 in. (460 mm) typical	1006	4	—	0.25	—
Straw bale[e] typically 16–24 in.	5–10	0.67–0.33	—	1.5–3.0	—
SIP (EPS)[f] various thicknesses	—	0.25	—	4	—
SIP (XPS)[g] various thicknesses	—	0.20	—	5	—
SIP (POLY/ISO)[h] various thicknesses	—	0.17–0.14	—	6–7	—
Insulating Materials					
Air krete[i]	2.2	0.26	—	3.9	
Insulating forms[j]	—	—	0.06–0.03		17–40
Part B: SI Units					
Description	**Density kg/m^2**	**Conductivity (k) W/m K**	**Conductance (C) W/m^2 K**	**Resistance Per Meter Thickness (1/k) K m/W**	**Resistance for Thickness Listed K m^2/W**
Building Materials					
Adobe[b] typically 250–610 mm	1600	0.476	—	2.1	—
Cob[c] typically 460–915 mm	—	0.577	—	1.7	—
Rammed earth[d] 460 mm typical	1600	0.577	—	1.7	—
Straw bale[e] typically 400–610 mm	80–160	0.097–0.048	—	10.4–20.8	—
SIP (EPS)[f] various thicknesses	—	0.036	—	27.7	—
SIP (XPS)[g] various thicknesses	—	0.029	—	34.7	—
SIP (POLY/ISO)[h] various thicknesses	—	0.025–0.02	—	41.6–48.5	—
Insulating Materials					
Air krete[i]	35	0.037	—	27.0	
Insulating forms[j]	—	—	0.34–0.17		3.0–7.0

[a]It is generally difficult to obtain reliable and consistent information on the thermal properties of alternative building materials that are not sold as a proprietary product. The data in this table have been obtained from a variety of sources (as noted); note the wide range of values and lack of data for some properties (such as specific heat).

[b]Adobe: U.S. Department of Energy, Office of Building Technology, State and Community Programs, *House of Straw — Straw Bale Construction Comes of Age*, http://www.grisb.org/publications/pub23.pdf

[c]Rammed earth: http://www.toolbase.org/

[d]Cob: http://www.toolbase.org/

[e]Straw bale: http://www.buildinggreen.com/news/r-value.cfm; recent tests suggest lower R-values than previously reported, with a typical R per inch of 1.5 for a per-bale R around 26–28.

[f]Structural insulated panel with expanded polystyrene insulation: http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm/mytopic=11740

[g]Structural insulated panel with extruded polystyrene insulation: http://www.eere.energy.gov/consumerinfo/factsheets/bd1.html

[h]Structural insulated panel with polyurethane/isocyanurate insulation: http://www.eere.energy.gov/consumerinfo/factsheets/bd1.html; R-values are for aged panels (as opposed to new panel R-values of 7–9 as typically reported).

[i]Air krete: http://www.airkrete.com/

[j]Insulating concrete forms come in a variety of configurations; the listed R-17 value is for a 9-inch wall section (4 in. polystyrene and 5 in. poured concrete); http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm/mytopic=11640

Another manufacturer produces forms that provide R-values of 22, 32, and 40.

TABLE E.3 Thermal Properties of Surface Air Films and Air Spaces

Part A. Surface Conductances[a] and Resistances[b] for Surface Air Films

		Surface Emittance, ε											
		I-P Units[c]						***SI Units[d]***					
		Nonreflective		**Reflective**				**Nonreflective**		**Reflective**			
		ε = **0.90**		ε = **0.20**		ε = **0.05**		ε = **0.90**		ε = **0.20**		ε = **0.05**	
Position of Surface	**Direction of Heat Flow**	h_i	**R**	h_i	**R**	h_i	**R**	h_i	**R**	h_i	**R**	h_i	**R**
Still Air													
Horizontal	Upward	1.63	0.61	0.91	1.10	0.76	1.32	9.26	0.11	5.17	0.19	4.32	0.23
Sloping–45°	Upward	1.60	0.62	0.88	1.14	0.73	1.37	9.09	0.11	5.00	0.20	4.15	0.24
Vertical	Horizontal	1.46	0.68	0.74	1.35	0.59	1.70	8.29	0.12	4.20	0.24	3.35	0.30
Sloping–45°	Downward	1.32	0.76	0.60	1.67	0.45	2.22	7.50	0.13	3.41	0.29	2.56	0.39
Horizontal	Downward	1.08	0.92	0.37	2.70	0.22	4.55	6.13	0.16	2.10	0.48	1.25	0.80
Moving Air (any position)		h_o	**R**					h_o	**R**				
Winter Wind													
15 mph (6.7 m/s)	Any	6.00	0.17					34.0	0.030				
Summer Wind													
7.5 mph (3.4 m/s)	Any	4.00	0.25					22.7	0.044				

Part B. Emittance Values of Various Surfaces and Effective Emittances of Air Spaces

	Effective Emittance ε_{EFF} of Air Space		
	Average Emittance ε	**One Surface Emittance ε; Other Surface 0.9**	**Both Surfaces Emittance ε**
Aluminum foil, bright	0.05	0.05	0.03
Aluminum foil with condensate just visible	0.30	0.29	—
Aluminum foil with condensate clearly visible	0.70	0.65	—
Aluminum sheet	0.12	0.12	0.06
Aluminum-coated paper, polished	0.20	0.20	0.11
Steel, galvanized, bright	0.25	0.24	0.15
Aluminum paint	0.50	0.47	0.35
Building materials: wood, paper, masonry, nonmetallic paints	0.90	0.82	0.82
Regular glass	0.84	0.77	0.72

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]Conductances are for surfaces of the stated emittance facing virtual blackbody surroundings at the same temperature as the ambient air. Values are based on a surface–air temperature difference of 10F° (5.5C°) and for surface temperatures of 70°F (21°C).

[b]No surface has both an air space resistance value and a surface resistance value.

[c]I-P units: surface conductance h_i and h_o measured in Btu/h ft^2 °F; resistance R measured in h ft^2 °F/Btu.

[d]SI units: surface conductance h_i and h_o measured in W/m^2 K; resistance R measured in m^2 K/W.

TABLE E.4 Thermal Resistances of Plane[a] Air Spaces (I-P Units)

All resistance are values expressed in ft^2 °F h/Btu. Values apply only to air spaces of uniform thickness bounded by plane, smooth, parallel surfaces with no leakage of air to or from the space. These conditions are not normally present in standard building construction. Thermal resistance values for multiple air spaces must be based on careful estimates of mean temperature differences for each air space.

Position of Air Space	Direction of Heat Flow	Air Space: Mean Temp,[b] °F	Air Space: Temp Diff,[b] F°	0.5-in. Air Space[d] Value of $E^{b,c}$: 0.03	0.05	0.2	0.5	0.82	0.75-in. Air Space[d] Value of $E^{b,c}$: 0.03	0.05	0.2	0.5	0.82
Horizontal	Up ↑	90	10	2.13	2.03	1.51	0.99	0.73	2.34	2.22	1.61	1.04	0.75
		50	30	1.62	1.57	1.29	0.96	0.75	1.71	1.66	1.35	0.99	0.77
		50	10	2.13	2.05	1.60	1.11	0.84	2.30	2.21	1.70	1.16	0.87
		0	20	1.73	1.70	1.45	1.12	0.91	1.83	1.79	1.52	1.16	0.93
		0	10	2.10	2.04	1.70	1.27	1.00	2.23	2.16	1.78	1.31	1.02
		–50	20	1.69	1.66	1.49	1.23	1.04	1.77	1.74	1.55	1.27	1.07
		–50	10	2.04	2.00	1.75	1.40	1.16	2.16	2.11	1.84	1.46	1.20
45° Slope	Up ↗	90	10	2.44	2.31	1.65	1.06	0.76	2.96	2.78	1.88	1.15	0.81
		50	30	2.06	1.98	1.56	1.10	0.83	1.99	1.92	1.52	1.08	0.82
		50	10	2.55	2.44	1.83	1.22	0.90	2.90	2.75	2.00	1.29	0.94
		0	20	2.20	2.14	1.76	1.30	1.02	2.13	2.07	1.72	1.28	1.00
		0	10	2.63	2.54	2.03	1.44	1.10	2.72	2.62	2.08	1.47	1.12
		–50	20	2.08	2.04	1.78	1.42	1.17	2.05	2.01	1.76	1.41	1.16
		–50	10	2.62	2.56	2.17	1.66	1.33	2.53	2.47	2.10	1.62	1.30
Vertical	Horizontal →	90	10	2.47	2.34	1.67	1.06	0.77	3.50	3.24	2.08	1.22	0.84
		50	30	2.57	2.46	1.84	1.23	0.90	2.91	2.77	2.01	1.30	0.94
		50	10	2.66	2.54	1.88	1.24	0.91	3.70	3.46	2.35	1.43	1.01
		0	20	2.82	2.72	2.14	1.50	1.13	3.14	3.02	2.32	1.58	1.18
		0	10	2.93	2.82	2.20	1.53	1.15	3.77	3.59	2.64	1.73	1.26
		–50	20	2.90	2.82	2.35	1.76	1.39	2.90	2.83	2.36	1.77	1.39
		–50	10	3.20	3.10	2.54	1.87	1.46	3.72	3.60	2.87	2.04	1.56
45° Slope	Down ↘	90	10	2.48	2.34	1.67	1.06	0.77	3.53	3.27	2.10	1.22	0.84
		50	30	2.64	2.52	1.87	1.24	0.91	3.43	3.23	2.24	1.39	0.99
		50	10	2.67	2.55	1.89	1.25	0.92	3.81	3.57	2.40	1.45	1.02
		0	20	2.91	2.80	2.19	1.52	1.15	3.75	3.57	2.63	1.72	1.26
		0	10	2.94	2.83	2.21	1.53	1.15	4.12	3.91	2.81	1.80	1.30
		–50	20	3.16	3.07	2.52	1.86	1.45	3.78	3.65	2.90	2.05	1.57
		–50	10	3.26	3.16	2.58	1.89	1.47	4.35	4.18	3.22	2.21	1.66

TABLE E.4 Thermal Resistances of Plane[a] Air Spaces (I-P Units) (*Continued*)

Position of Air Space	Direction of Heat Flow		*Air Space* Mean Temp,[b] °F	Temp Diff,[b] F°	*0.5-in. Air Space[d]* *Value of E[b,c]* 0.03	0.05	0.2	0.5	0.82	*0.75-in. Air Space[d]* *Value of E[b,c]* 0.03	0.05	0.2	0.5	0.82
Horizontal	Down	↓	90	10	2.48	2.34	1.67	1.06	0.77	3.55	3.29	2.10	1.22	0.85
			50	30	2.66	2.54	1.88	1.24	0.91	3.77	3.52	2.38	1.44	1.02
			50	10	2.67	2.55	1.89	1.25	0.92	3.84	3.59	2.41	1.45	1.02
			0	20	2.94	2.83	2.20	1.53	1.15	4.18	3.96	2.83	1.81	1.30
			0	10	2.96	2.85	2.22	1.53	1.16	4.25	4.02	2.87	1.82	1.31
			–50	20	3.25	3.15	2.58	1.89	1.47	4.60	4.41	3.36	2.28	1.69
			–50	10	3.28	3.18	2.60	1.90	1.47	4.71	4.51	3.42	2.30	1.71

Position of Air Space	Direction of Heat Flow		Air Space Mean Temp,[b] °F	Temp Diff,[b] F°	1.5-in. Air Space[d] Value of E[b,c] 0.03	0.05	0.2	0.5	0.82	3.5-in. Air Space[d] Value of E[b,c] 0.03	0.05	0.2	0.5	0.82
Horizontal	Up	↑	90	10	2.55	2.41	1.71	1.08	0.77	2.84	2.66	1.83	1.13	0.80
			50	30	1.87	1.81	1.45	1.04	0.80	2.09	2.01	1.58	1.10	0.84
			50	10	2.50	2.40	1.81	1.21	0.89	2.80	2.66	1.95	1.28	0.93
			0	20	2.01	1.95	1.63	1.23	0.97	2.25	2.18	1.79	1.32	1.03
			0	10	2.43	2.35	1.90	1.38	1.06	2.71	2.62	2.07	1.47	1.12
			–50	20	1.94	1.91	1.68	1.36	1.13	2.19	2.14	1.86	1.47	1.20
			–50	10	2.37	2.31	1.99	1.55	1.26	2.65	2.58	2.18	1.67	1.33
45° Slope	Up	↗	90	10	2.92	2.73	1.86	1.14	0.80	3.18	2.96	1.97	1.18	0.82
			50	30	2.14	2.06	1.61	1.12	0.84	2.26	2.17	1.67	1.15	0.86
			50	10	2.88	2.74	1.99	1.29	0.94	3.12	2.95	2.10	1.34	0.96
			0	20	2.30	2.23	1.82	1.34	1.04	2.42	2.35	1.90	1.38	1.06
			0	10	2.79	2.69	2.12	1.49	1.13	2.98	2.87	2.23	1.54	1.16
			–50	20	2.22	2.17	1.88	1.49	1.21	2.34	2.29	1.97	1.54	1.25
			–50	10	2.71	2.64	2.23	1.69	1.35	2.87	2.79	2.33	1.75	1.39
Vertical	Horizontal	→	90	10	3.99	3.66	2.25	1.27	0.87	3.69	3.40	2.15	1.24	0.85
			50	30	2.58	2.46	1.84	1.23	0.90	2.67	2.55	1.89	1.25	0.91
			50	10	3.79	3.55	2.39	1.45	1.02	3.63	3.40	2.32	1.42	1.01
			0	20	2.76	2.66	2.10	1.48	1.12	2.88	2.78	2.17	1.51	1.14
			0	10	3.51	3.35	2.51	1.67	1.23	3.49	3.33	2.50	1.67	1.23
			–50	20	2.64	2.58	2.18	1.66	1.33	2.82	2.75	2.30	1.73	1.37
			–50	10	3.31	3.21	2.62	1.91	1.48	3.40	3.30	2.67	1.94	1.50

45° Slope	Down	↘	90	10	5.07	4.55	2.56	1.36	0.91	4.81	4.33	2.49	1.34	0.90
			50	30	3.58	3.36	2.31	1.42	1.00	3.51	3.30	2.28	1.40	1.00
			50	10	5.10	4.66	2.85	1.60	1.09	4.74	4.36	2.73	1.57	1.08
			0	20	3.85	3.66	2.68	1.74	1.27	3.81	3.63	2.66	1.74	1.27
			0	10	4.92	4.62	3.16	1.94	1.37	4.59	4.32	3.02	1.88	1.34
			–50	20	3.62	3.50	2.80	2.01	1.54	3.77	3.64	2.90	2.05	1.57
			–50	10	4.67	4.47	3.40	2.29	1.70	4.50	4.32	3.31	2.25	1.68
Horizontal	Down	↓	90	10	6.09	5.35	2.79	1.43	0.94	10.07	8.19	3.41	1.57	1.00
			50	30	6.27	5.63	3.18	1.70	1.14	9.60	8.17	3.86	1.88	1.22
			50	10	6.61	5.90	3.27	1.73	1.15	11.15	9.27	4.09	1.93	1.24
			0	20	7.03	6.43	3.91	2.19	1.49	10.90	9.52	4.87	2.47	1.62
			0	10	7.31	6.66	4.00	2.22	1.51	11.97	10.32	5.08	2.52	1.64
			–50	20	7.73	7.20	4.77	2.85	1.99	11.64	10.49	6.02	3.25	2.18
			–50	10	8.09	7.52	4.91	2.89	2.01	12.98	11.56	6.36	3.34	2.22

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]Thermal resistance values were determined from the relation R = 1/C, where $C = h_c + \varepsilon_{eff}\, h_r$; h_c is the conduction–convection coefficient; $\varepsilon_{eff}\, h_r$ is the radiation coefficient $= 0.0068\varepsilon_{eff}[(t_m + 460)/100]^3$; and t_m is the mean temperature of the air space. For extrapolation from this table to air spaces less than 0.5 in. (as in insulating window glass), assume that $h_c = 0.159(1 + 0.0016t_m)/l$, where l is the air space thickness in inches and h_c is heat transfer through the air space only.

[b]Interpolation is permissible for other values of mean temperature, temperature difference, and effective emittance ε_{eff}. Interpolation and moderate extrapolation for air spaces greater than 3.5 in. are also permissible.

[c]Effective emittance, ε_{eff}, of the air space is given by $1/\varepsilon_{eff} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$, where ε_1 and ε_2 are emittances of the surfaces of the air space (from Table E.3).

[d]A single resistance value cannot account for multiple air spaces. Each air space requires a separate resistance calculation that applies only for the established boundary conditions.

[e]Resistances of horizontal spaces with heat flow downward are substantially independent of temperature difference.

TABLE E.5 Thermal Resistances of Plane[a] Air Spaces (SI Units)

All resistance values are expressed in K m^2/W. Values apply only to air spaces of uniform thickness bounded by plane, smooth, parallel surfaces with no leakage of air to or from the space. These conditions are not normally present in standard building construction. Thermal resistance values for multiple air spaces must be based on careful estimates of mean temperature differences for each air space.

Position of Air Space	Direction of Heat Flow		Air Space: Mean Temp,[b] °C	Air Space: Temp Diff,[b] C°	13-mm Air Space[d] Value of E[b,c] 0.03	0.05	0.2	0.5	0.82	20-mm Air Space[d] Value of E[b,c] 0.03	0.05	0.2	0.5	0.82
Horizontal	Up	↑	32.2	5.6	0.37	0.36	0.27	0.17	0.13	0.41	0.39	0.28	0.18	0.13
			10.0	16.7	0.29	0.28	0.23	0.17	0.13	0.30	0.29	0.24	0.17	0.14
			10.0	5.6	0.37	0.36	0.28	0.30	0.15	0.40	0.39	0.30	0.20	0.15
			–17.8	11.1	0.30	0.30	0.26	0.20	0.16	0.32	0.32	0.27	0.20	0.16
			–17.8	5.6	0.37	0.36	0.30	0.22	0.18	0.39	0.38	0.31	0.23	0.18
			–45.6	11.1	0.30	0.29	0.26	0.22	0.18	0.31	0.31	0.27	0.22	0.19
			–45.6	5.6	0.36	0.35	0.31	0.25	0.20	0.38	0.37	0.32	0.26	0.21
45° Slope	Up	↗	32.2	5.6	0.43	0.41	0.29	0.19	0.13	0.52	0.49	0.33	0.20	0.14
			10.0	16.7	0.36	0.35	0.27	0.19	0.15	0.35	0.34	0.27	0.19	0.14
			10.0	5.6	0.45	0.43	0.32	0.21	0.16	0.51	0.48	0.35	0.23	0.17
			–17.8	11.1	0.39	0.38	0.31	0.23	0.18	0.37	0.36	0.30	0.23	0.18
			–17.8	5.6	0.46	0.45	0.36	0.25	0.19	0.48	0.46	0.37	0.26	0.20
			–45.6	11.1	0.37	0.36	0.31	0.25	0.21	0.36	0.35	0.31	0.25	0.20
			–45.6	5.6	0.46	0.45	0.38	0.29	0.23	0.45	0.43	0.37	0.29	0.23
Vertical	Horizontal	→	32.2	5.6	0.43	0.41	0.29	0.19	0.14	0.62	0.57	0.37	0.21	0.15
			10	16.7	0.45	0.43	0.32	0.22	0.16	0.51	0.49	0.35	0.23	0.17
			10	5.6	0.47	0.45	0.33	0.22	0.16	0.65	0.61	0.41	0.25	0.18
			–17.8	11.1	0.50	0.48	0.38	0.26	0.20	0.55	0.53	0.41	0.28	0.21
			–17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
			–45.6	11.1	0.51	0.50	0.41	0.31	0.24	0.51	0.50	0.42	0.31	0.24
			–45.6	5.6	0.56	0.55	0.45	0.33	0.26	0.65	0.63	0.51	0.36	0.27
45° Slope	Down	↘	32.2	5.6	0.44	0.41	0.29	0.19	0.14	0.62	0.58	0.37	0.21	0.15
			10.0	16.7	0.46	0.44	0.33	0.22	0.16	0.60	0.57	0.39	0.24	0.17
			10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.67	0.63	0.42	0.26	0.18
			–17.8	11.1	0.51	0.49	0.39	0.27	0.20	0.66	0.63	0.46	0.30	0.22
			–17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.73	0.69	0.49	0.32	0.23
			–45.6	11.1	0.56	0.54	0.44	0.33	0.25	0.67	0.64	0.51	0.36	0.28
			–45.6	5.6	0.57	0.56	0.45	0.33	0.26	0.77	0.74	0.57	0.39	0.29

Horiz.	Down	↓	32.2	5.6	0.44	0.41	0.29	0.19	0.14	0.62	0.58	0.37	0.21	0.15
			10.0	16.7	0.47	0.45	0.33	0.22	0.16	0.66	0.62	0.42	0.25	0.18
			10.0	5.6	0.47	0.45	0.33	0.22	0.16	0.68	0.63	0.42	0.26	0.18
			–17.8	11.1	0.52	0.50	0.39	0.27	0.20	0.74	0.70	0.50	0.32	0.23
			–17.8	5.6	0.52	0.50	0.39	0.27	0.20	0.75	0.71	0.51	0.32	0.23
			–45.6	11.1	0.57	0.55	0.45	0.33	0.26	0.81	0.78	0.59	0.40	0.30
			–45.6	5.6	0.58	0.56	0.46	0.33	0.26	0.83	0.79	0.60	0.40	0.30

Position of Air Space	Direction of Heat Flow		*Air Space* Mean Temp,[b] °C	Temp Diff,[b] C°	*40-mm Air Space*[d] *Value of* $E^{b,c}$ 0.03	0.05	0.2	0.5	0.82	*90-mm Air Space*[d] *Value of* $E^{b,c}$ 0.03	0.05	0.2	0.5	0.82
Horizontal	Up	↑	32.2	5.6	0.45	0.42	0.30	0.19	0.14	0.50	0.47	0.32	0.20	0.14
			10.0	16.7	0.33	0.32	0.26	0.18	0.14	0.27	0.35	0.28	0.19	0.15
			10.0	5.6	0.44	0.42	0.32	0.21	0.16	0.49	0.47	0.34	0.23	0.16
			–17.8	11.1	0.35	0.34	0.29	0.22	0.17	0.40	0.38	0.32	0.23	0.18
			–17.8	5.6	0.43	0.41	0.33	0.24	0.19	0.48	0.46	0.36	0.26	0.20
			–45.6	11.1	0.34	0.34	0.30	0.24	0.20	0.39	0.38	0.33	0.26	0.21
			–45.6	5.6	0.42	0.41	0.35	0.27	0.22	0.47	0.45	0.38	0.29	0.23
45° Slope	Up	↗	32.2	5.6	0.51	0.48	0.33	0.20	0.14	0.56	0.52	0.35	0.21	0.14
			10.0	16.7	0.38	0.36	0.28	0.20	0.15	0.40	0.38	0.29	0.20	0.15
			10.0	5.6	0.51	0.48	0.35	0.23	0.17	0.55	0.52	0.37	0.24	0.17
			–17.8	11.1	0.40	0.39	0.32	0.24	0.18	0.43	0.41	0.33	0.24	0.19
			–17.8	5.6	0.49	0.47	0.37	0.26	0.20	0.52	0.51	0.39	0.27	0.20
			–45.6	11.1	0.39	0.38	0.33	0.26	0.21	0.41	0.40	0.35	0.27	0.22
			–45.6	5.6	0.48	0.46	0.39	0.30	0.24	0.51	0.49	0.41	0.31	0.24
Vertical	Horizontal	→	32.2	5.6	0.70	0.64	0.40	0.22	0.15	0.65	0.60	0.38	0.22	0.15
			10.0	16.7	0.45	0.43	0.32	0.22	0.16	0.47	0.45	0.33	0.22	0.16
			10.0	5.6	0.67	0.62	0.42	0.26	0.18	0.64	0.60	0.41	0.25	0.18
			–17.8	11.1	0.49	0.47	0.37	0.26	0.20	0.51	0.49	0.38	0.27	0.20
			–17.8	5.6	0.62	0.59	0.44	0.29	0.22	0.61	0.59	0.44	0.29	0.22
			–45.6	11.1	0.46	0.45	0.38	0.29	0.23	0.50	0.48	0.40	0.30	0.24
			–45.6	5.6	0.58	0.56	0.46	0.34	0.26	0.60	0.58	0.47	0.34	0.26

TABLE E.5 Thermal Resistances of Plane[a] Air Spaces (SI Units) (*Continued*)

Position of Air Space	Direction of Heat Flow		Air Space: Mean Temp,[b] °C	Air Space: Temp Diff,[b] C°	40-mm Air Space[d] Value of $E^{b,c}$: 0.03	0.05	0.2	0.5	0.82	90-mm Air Space[d] Value of $E^{b,c}$: 0.03	0.05	0.2	0.5	0.82
45° Slope	Down	↘	32.2	5.6	0.89	0.80	0.45	0.24	0.16	0.85	0.76	0.44	0.24	0.16
			10.0	16.7	0.63	0.59	0.41	0.25	0.18	0.62	0.58	0.40	0.25	0.18
			10.0	5.6	0.90	0.82	0.50	0.28	0.19	0.83	0.77	0.48	0.28	0.19
			–17.8	11.1	0.68	0.64	0.47	0.31	0.22	0.67	0.64	0.47	0.31	0.22
			–17.8	5.6	0.87	0.81	0.56	0.34	0.24	0.81	0.76	0.53	0.33	0.24
			–45.6	1.1	0.64	0.62	0.49	0.35	0.27	0.66	0.64	0.51	0.36	0.28
			–45.6	5.6	0.82	0.79	0.60	0.40	0.30	0.79	0.76	0.58	0.40	0.30
Horizontal	Down	↓	32.2	5.6	1.07	0.94	0.49	0.25	0.17	1.77	1.44	0.60	0.28	0.18
			10.0	16.7	1.10	0.99	0.56	0.30	0.20	1.69	1.44	0.68	0.33	0.21
			10.0	5.6	1.16	1.04	0.58	0.30	0.20	1.96	1.63	0.72	0.34	0.22
			–17.8	11.1	1.24	1.13	0.69	0.39	0.26	1.92	1.68	0.86	0.4	0.29
			–17.8	5.6	1.29	1.17	0.70	0.39	0.27	2.11	1.82	0.89	0.44	0.29
			–45.6	11.1	1.36	1.27	0.84	0.50	0.35	2.05	1.85	1.06	0.57	0.38
			–45.6	5.6	1.42	1.32	0.86	0.51	0.35	2.28	2.03	1.12	0.59	0.39

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]Thermal resistance values were determined from the relation R = 1/C, where C = $h_c + \varepsilon_{eff}\, h_r$; h_c is the conduction–convection coefficient; $\varepsilon_{eff}\, h_r$ is the radiation coefficient = $0.227\varepsilon_{eff}[(t_m + 273)/100]^3$; and t_m is the mean temperature of the air space. For extrapolation from this table to air spaces less than 12.5 mm (as in insulating window glass), assume that $h_c = 21.8\ (1 + 0.00274 t_m)/l$, where l is the air space thickness in inches, and h_c is the heat transfer in W/m^2 K through the air space only.

[b]Interpolation is permissible for other values of mean temperature, temperature difference, and effective emittance e_{eff}. Interpolation and moderate extrapolation for air spaces greater than 90 mm are also permissible.

[c]Effective emittance, ε_{eff}, of the air space is given by $1/\varepsilon_{eff} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$, where ε_1 and ε_2 are emittances of the surfaces of the air space (from Table E.3).

[d]A single resistance value cannot account for multiple air spaces. Each air space requires a separate resistance calculation that applies only for the established boundary conditions.

[e]Resistances of horizontal spaces with heat flow downward are substantially independent of temperature difference.

TABLE E.6 U-Factors for Common Wall, Roof, and Floor Assemblies

Assembly	Basic Construction	Other Thermal Components	*I-P* Insulation R-value °F ft² h/Btu	*SI* Insulation R-value K m²/W	*I-P* Assembly U-factor Btu/°F ft² h	*SI* Assembly U-factor W/K m²
Wall	Wood studs, nominal 2 in. × 4 in., 16 in. o.c. (50 mm × 100 mm, 400 mm o.c.)	Exterior air film, stucco, exterior gypsum board, interior gypsum board, interior air film	11	1.94	0.096	0.55
	As above	Above plus R-4 (SI: R-0.7) continuous insulation	15	2.64	0.068	0.39
	Wood studs, nominal 2 in. × 6 in., 24 in. o.c. (50 mm × 150 mm, 400 mm o.c.)		18	3.17	0.065	0.37
	Steel studs, nominal 2 in. × 4 in., 16 in. o.c. (50 mm × 100 mm, 400 mm o.c.)		11	1.94	0.132	0.75
	As above	Above plus R-4 (SI: R-0.7) continuous insulation	15	2.64	0.087	0.49
	6-in. concrete masonry unit at 115 lb/ft³ (150 mm, at 1840 kg/m³)	Partly grouted, cells insulated	N/A	N/A	0.41	2.33
	As above	Above with R-4 (SI: R-0.7) continuous insulation with 1-in. (25-mm) framing and interior gypsum board	4	0.70	0.17	0.97
Roof	Standard wood joists	Semiexterior air film, gypsum board, interior air film	30	5.28	0.034	0.19
	Steel joists	Exterior air film, metal deck, interior air film	30	5.28	0.041	0.23
	System with insulation entirely above roof deck	Exterior air film, metal deck, interior air film	30	5.28	0.032	0.18
Floor	Nominal 6-in. wood joists (150 mm)	Semiexterior air film, wood subfloor, carpet and pad, interior film air	11	1.94	0.074	0.42
	Steel floor joists	Semiexterior air film, metal deck, concrete slab, carpet and pad, interior air film	11	1.94	0.078	0.44

Source: Extracted and used with permission; ©ASHRAE, ANSI/ASHRAE/IESNA Standard 90.1-2013: *Energy Standard for Buildings Except Low-Rise Residential Buildings*

Note: The SI units for resistance and U-factor were appended to the ASHRAE I-P data by the authors.

TABLE E.7 U-Factors for Walls in Passive Solar Heating Systems

	Whole-Assembly U-Factor, Winter					
	No Night Insulation		*With Night Insulation[a] of Specified R*			
	I-P	*SI*	*I-P*	*SI*	*I-P*	*SI*
			R-4	SI:R-0.7	R-9	SI:R-1.58
Component	**Btu / °F ft² h**	**W / K m²**	**Btu / °F ft² h**	**W / K m²**	**Btu / °F ft² h**	**W / K m²**
Direct gain[b]	0.55	3.1	0.30	1.7	0.24	1.4
Trombe wall, 18-in. (460-mm) thick[b]	0.22	1.2	0.15	0.9	0.12	0.7
Water wall[b]	0.33	1.9	0.20	1.1	0.17	1.0

[a]These are daily average U-factors rather than the instantaneous U-factors generally presented in these tables. Insulation is assumed to be in place from 5:00 P.M. to 8:00 A.M., solar time, for Trombe and water walls and 5:00 P.M. to 7:00 A.M. for direct gain.

[b]From J. D. Balcomb et al., *Passive Solar Design Handbook*, Volume Two: *Passive Solar Design Analysis* (1980). U.S. Department of Energy, Washington, DC. SI values were appended to the I-P data by the authors.

TABLE E.8 Effective R-Values for Wall, Roof, and Floor Systems with Steel Framing

Construction	Spacing of Framing	*Cavity Insulation R-value* *I-P* °F ft² h/Btu	*SI* K m²/W	Correction Factor[a, b]	*Effective Framing/Insulation R-value* *I-P* °F ft² h/Btu	*SI* K m²/W
Walls						
Nominal Cavity Depth (Stud Size)						
4 in. (100 mm)	16 in. (400 mm) o.c.	11	1.94	0.50	5.5	0.96
		13	2.29	0.46	6.0	1.06
		15	2.64	0.43	6.4	1.13
4 in. (100 mm)	24 in. (600 mm) o.c.	11	1.94	0.60	6.6	1.16
		13	2.29	0.55	7.2	1.27
		15	2.64	0.52	7.8	1.37
6 in. (150 mm)	16 in. (400 mm) o.c.	19	3.35	0.37	7.1	1.25
		21	3.70	0.35	7.4	1.30
6 in. (150 mm)	24 in. (600 mm) o.c.	19	3.35	0.45	8.6	1.52
		21	3.70	0.43	9.0	1.59
8 in. (200 mm)	16 in. (400 mm) o.c.	25	4.41	0.31	7.8	1.37
8 in. (200 mm)	24 in. (600 mm) o.c.	25	4.41	0.38	9.6	1.69
Roofs/Floors						
Insulation *R*	4 ft (1.2 m) o.c.					
11		11	1.94	0.91	10.0	1.76
13		13	2.29	0.90	11.7	2.06
15		15	2.64	0.88	13.2	2.32
19		19	3.35	0.86	16.3	2.87
21		21	3.70	0.84	17.6	3.10
25		25	4.41	0.81	20.2	3.56
30		30	5.28	0.79	23.7	4.17
35		35	6.16	0.76	26.6	4.68
40		40	7.04	0.73	29.2	5.14
45		45	7.92	0.71	32.0	5.63
50		50	8.80	0.69	34.5	6.07
55		55	9.68	0.67	36.9	6.49

Source: Reprinted with permission; ©ASHRAE, ANSI/ASHRAE/IESNA Standard 90.1-2013: *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

Note: The SI units for resistance were appended to the ASHRAE I-P data by the authors.

[a]Correction factors for walls are from Standard 90.2.

[b]Roof/floor correction factors are from Standard 90.1 and are based upon 4-ft (1.2-m) o.c. metal trusses that penetrate the insulation and 0.66-in. (16.8-mm) crossbars every 1 ft (0.3 m).

TABLE E.9 Comparison of U-Factors for Framed Walls and Structural Insulated Panels (SIP)

Component	*Cavity R-Value*[a]		*Center-of-Insulated Whole-Wall R-Value*[b]		*Wall U-Factor*[c]	
	I-P	***SI***	***I-P***	***SI***	***I-P***	***SI***
	°F ft^2 h/ Btu	**K m^2/ W**	**°F ft^2 h/ Btu**	**K m^2/ W**	**Btu/ °F ft^2 h**	**W/ k m^2**
2-in. × 4-in. insulated stud wall at 16-in. o.c. (50 × 100 mm at 400 mm)	13.6	2.40	9.6	1.69	0.104	0.59
2-in. × 6-in. insulated stud wall at 24-in. o.c. (50 × 150 mm at 600 mm)	19.6	3.46	13.7	2.41	0.073	0.41
6½-in. SIP (165 mm)	25.1	4.35	21.6	3.80	0.046	0.26

Source: Oak Ridge National Laboratory (in *Environmental Building News* 7(5) May 1998).

[a]Center-of-insulated-cavity R-value is the maximum total R-value through a cross section of the wall system, including insulation, sheathing, drywall, etc.

[b]Whole-wall R-value is an average value that includes adjustments for the framing as well as some openings in a standardized wall system.

[c]U-factors calculated by the authors and appended to Oak Ridge R-value data; SI dimensions also appended by the authors.

TABLE E.10 Transmission Coefficients (U-Factors) for Wood and Steel Doors

Nominal Door Thickness			Wood Storm Door[a]		Metal Storm Door[b]		No Storm Door	
			I-P	SI	I-P	SI	I-P	SI
in.	mm		Btu/h ft^2 °F	W/m^2 K	Btu/h ft^2 °F	W/m^2 K	Btu/h ft^2 °F	W/m^2 K
Unglazed Wood Doors[c, d]								
1⅜	35	Panel door with 7/16-in. (11-mm) panels[e]	0.33	1.87	0.37	2.10	0.57	3.24
1⅜	35	Hollow core flush door	0.30	1.70	0.32	1.82	0.47	2.67
1⅜	35	Solid core flush door	0.26	1.48	0.28	1.59	0.39	2.21
1¾	45	Panel door with 7/16-in. (11-mm) panels	0.32	1.82	0.36	2.04	0.54	3.07
1¾	45	Hollow core flush door	0.29	1.65	0.32	1.82	0.46	2.61
1¾	45	Panel door with 1⅛-in. (29-mm) panels	0.26	1.48	0.28	1.59	0.39	2.21
1¾	45	Solid core flush door	—	—	0.26	1.48	0.40	2.27
2¼	57	Solid core flush door	0.20	1.14	0.21	1.19	0.27	1.53
Unglazed Steel Doors[d]								
1¾	45	Fiberglass or mineral wool core with steel stiffeners, no thermal break[f]			—	—	0.60	3.41
1¾	45	Paper honeycomb core without thermal break[f]			—	—	0.56	3.18
1¾	45	Solid urethane foam core without thermal break[c]			—	—	0.40	2.27
1¾	45	Solid fire-rated mineral fiberboard core without thermal break[f]			—	—	0.38	2.16
1¾	45	Polystyrene core without thermal break[f] (18-gage [1.31-mm] commercial steel)			—	—	0.35	1.99
1¾	45	Polyurethane core without thermal break[f] (24-gage [0.70-mm] residential steel)			—	—	0.29	1.65
1¾	45	Polyurethane core with thermal break and wood perimeter[f] (24-gage [0.70-mm] residential steel)			—	—	0.20	1.14
1¾	45	Solid urethane foam core with thermal break[c]			0.16	0.91	0.20	1.14

Source: Previously adapted, with the permission of ASHRAE, from the *2001 ASHRAE Handbook—Fundamentals* (Chapter 25, Table 6). This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

Note: U-factors listed are for exterior doors with no glazing, except for the storm doors, which are in addition to the main exterior door. Any glazing area in exterior doors should be included with the appropriate glass type and analyzed as a window (see Table E.14). Interpolation and moderate extrapolation are permitted for door thicknesses other than those specified.

[a]Values for wood storm door are approximately 50% glass.

[b]Values for metal storm door are for any percentage of glass area.

[c]Values are based on a nominal 32-in. × 80-in. (810-mm × 2030-mm) door size with no glazing.

[d]Outside air conditions: 15 mph (24 km/h) wind speed, 0°F (–18°C) air temperature; inside air conditions: natural convection, 70°F (21°C) air temperature.

[e]A 55% panel area.

[f]ASTM C 236 hot box data on a nominal 3-ft × 7-ft (910-mm × 2130-mm) door size with no glazing.

TABLE E.11 Heat Loss Coefficients (F_2) for Slab-on-Grade Floors

		I-P ***Btu/h °F ft Perimeter Degree Days (65°F base)***			***SI*** ***W/K m Perimeter Degree Days (18°C base)***		
Construction[a]	**Insulation**	**2950**	**5350**	**7433**	**1640**	**2970**	**4130**
(a) Block wall, 8 in. (200 mm), brick facing	Uninsulated	0.62	0.68	0.72	1.07	1.17	1.24
	Insulated from edge to footer: R-5.4 h ft^2 °F/Btu (SI: R-0.95 m^2 K/W)	0.48	0.50	0.56	0.83	0.86	0.97
(b) Block wall, 4 in. (100 mm), brick facing	Uninsulated	0.80	0.84	0.93	1.38	1.45	1.61
	Insulated from edge to footer: R-5.4 h ft^2 °F/Btu (SI: R-0.95 m^2 K/W)	0.47	0.49	0.54	0.81	0.85	0.93
(c) Metal stud wall, stucco	Uninsulated	1.15	1.20	1.34	1.99	2.07	2.32
	Insulated from edge to footer: R-5.4 h ft^2 °F/Btu (SI: R-0.95 m^2 K/W)	0.51	0.53	0.58	0.88	0.92	1.00
(d) Poured concrete wall with duct near perimeter[b]	Uninsulated	1.84	2.12	2.73	3.18	3.67	4.72
	Insulated from edge to footer, and 3 ft. [910 mm] under floor slab R-5.4 h ft^2 °F/Btu (SI: R-0.95 m^2 K/W)	0.64	0.72	0.90	1.11	1.24	1.56

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*. The SI units for F_2 shown in the last three columns were appended to the ASHRAE I-P data by the authors.

[a]See Fig. E.1 for illustrations of the listed constructions.

[b]Weighted average temperature of heating duct was assumed to be 110°F (43°C) during the heating season (outdoor air temperature less than 65°F [18°C]).

Note: To use this table:

$$q = F_2 P \Delta t$$

where

q = heat loss through perimeter (Btu/h or W)
F_2 = heat loss coefficients from above
P = perimeter of exposed slab edge (ft or m)
Δt = temperature difference between indoor and outdoor air (°F or °C).

Do not assume additional losses from the slab to the earth below. Heat gains are assumed to be nonexistent.

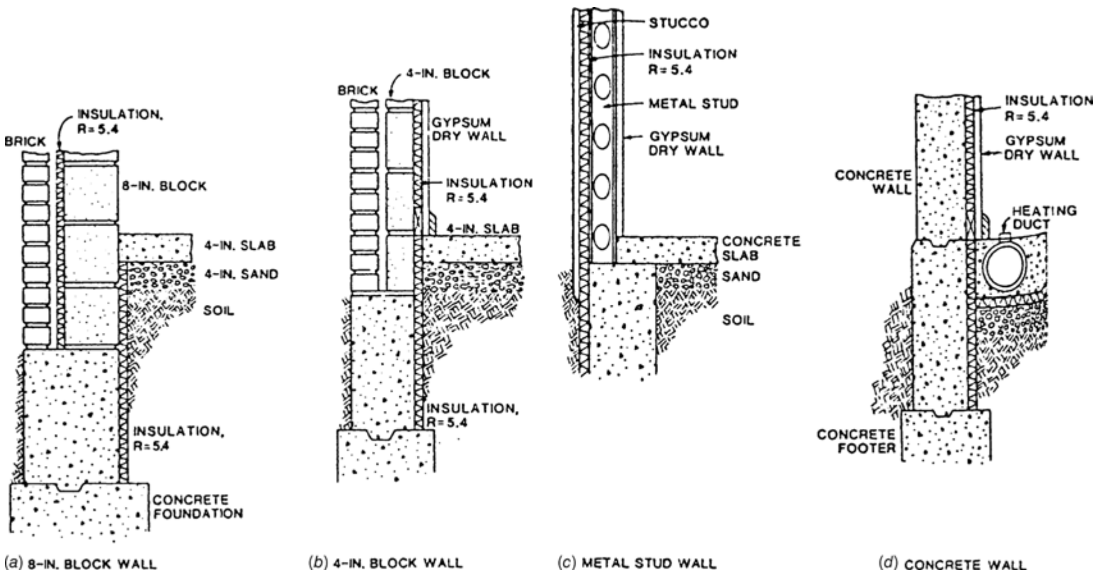


Fig. E.1 *Insulation and construction configurations for Table E.11 data (heat loss coefficients for slab-on-grade floors). Previously adapted, with the permission of ASHRAE, from the* 2001 ASHRAE Handbook—Fundamentals. *This citation to an older version of the* Handbook *is intentional and provides access to historic reference information of ongoing interest.*

TABLE E.12 Heat Flow Coefficients (F_2) for Slab-on-Grade Floors with Various Insulation Strategies

	F_2	
	I-P	***SI***
R-Value, Position, and Width (or Depth) of Insulation	**Btu/h ft °F**	**W/m K**
Uninsulated slab	0.73	1.26
R-5 (SI: R-0.88) Horizontal insulation, 2 ft (0.6 m), no thermal break	0.70	1.21
R-10 (SI: R-1.76) Horizontal insulation, 2 ft (0.6 m), no thermal break	0.70	1.21
R-15 (SI: R-2.64) Horizontal insulation, 2 ft (0.6 m), no thermal break	0.69	1.19
R-5 (SI: R-0.88) Horizontal insulation, 4 ft (1.2 m), no thermal break	0.67	1.16
R-10 (SI: R-1.76) Horizontal insulation, 4 ft (1.2 m), no thermal break	0.64	1.11
R-15 (SI: R-2.64) Horizontal insulation, 4 ft (1.2 m), no thermal break	0.63	1.09
R-5 (SI: R-0.88) Vertical insulation, 2 ft (0.6 m)	0.58	1.00
R-10 (SI: R-1.76) Vertical insulation, 2 ft (0.6 m)	0.54	0.93
R-15 (SI: R-2.64) Vertical insulation, 2 ft (0.6 m)	0.52	0.90
R-5 (SI: R-0.88) Vertical insulation, 4 ft (1.2 m)	0.54	0.93
R-10 (SI: R-1.76) Vertical insulation, 4 ft (1.2 m)	0.48	0.83
R-15 (SI: R-2.65) Vertical insulation, 4 ft (1.2 m)	0.45	0.78
R-10 (SI: R-1.76) Fully insulated slab (insulated under entire slab as well as around edge)	0.36	0.62

Source: Reprinted with permission; ©ASHRAE, ANSI/ASHRAE/IESNA Standard 90.1-2013: *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

Insulation is extruded polystyrene, R = 5.0 h ft^2 °F/Btu-in. (SI: R = 34.7 m K/W).

Soil conductivity is 0.75 Btu/h ft °F (1.30 W/K m).

No thermal break at edge of slab, where so indicated. If a thermal break is provided with horizontal insulation, use the corresponding value for vertical insulation.

Values assume an unheated slab; F_2 values increase substantially when slab is heated.

TABLE E.13 Heat Flow through Below-Grade Walls and Floors[a]

I-P Units

Part A: Average U-Factor for Basement Walls with Uniform Insulation				
	$U_{avg,bw}$ *from Grade to Depth, Btu/h·ft²·°F*			
Depth, ft	**Uninsulated**	**R-5**	**R-10**	**R-15**
1	0.432	0.135	0.080	0.057
2	0.331	0.121	0.075	0.054
3	0.273	0.110	0.070	0.052
4	0.235	0.101	0.066	0.050
5	0.208	0.094	0.063	0.048
6	0.187	0.088	0.060	0.046
7	0.170	0.083	0.057	0.044
8	0.157	0.078	0.055	0.043

Part B: Average U-Factor for Basement Floors				
	$U_{avg,bf}$, *Btu/h·ft²·°F*			
	w_b (Shortest Width of Basement), ft			
Depth of Floor Below Grade, ft	**20**	**24**	**28**	**32**
1	0.064	0.057	0.052	0.047
2	0.054	0.048	0.044	0.040
3	0.047	0.042	0.039	0.036
4	0.042	0.038	0.035	0.033
5	0.038	0.035	0.032	0.030
6	0.035	0.032	0.030	0.028
7	0.032	0.030	0.028	0.026

SI Units

Part A: Average U-Factor for Basement Walls with Uniform Insulation				
	$U_{avg,bw}$ *from Grade to Depth, W/m²·K*			
Depth, m	**Uninsulated**	**R-0.88**	**R-1.76**	**R-2.64**
0.3	2.468	0.769	0.458	0.326
0.6	1.898	0.689	0.427	0.310
0.9	1.571	0.628	0.401	0.296
1.2	1.353	0.579	0.379	0.283
1.5	1.195	0.539	0.360	0.272
1.8	1.075	0.505	0.343	0.262
2.1	0.980	0.476	0.328	0.252
2.4	0.902	0.450	0.315	0.244

Part B: Average U-Factor for Basement Floors				
	$U_{avg,bf}$, *W/m²·K*			
	w_b *(Shortest Width of Basement), m*			
Depth of Floor Below Grade, m	**6**	**7**	**8**	**9**
0.3	0.370	0.335	0.307	0.283
0.6	0.310	0.283	0.261	0.242
0.9	0.271	0.249	0.230	0.215
1.2	0.242	0.224	0.208	0.195
1.5	0.220	0.204	0.190	0.179
1.8	0.202	0.188	0.176	0.166
2.1	0.187	0.175	0.164	0.155

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]Only heat losses are assumed because the interior temperature is normally higher than the ground temperature.

[b]Soil conductivity assumed to be 1.4 W/m K (0.8 Btu /h ft °F).

TABLE E.14 U-Factors of Representative Window Assemblies

Glazing System Description	Aluminum without Thermal Break I-P: Btu/h ft^2 °F SI: W/m^2 K	Aluminum with Thermal Break I-P: Btu/h ft^2 °F SI: W/m^2 K	Insulated Wood/ Vinyl I-P: Btu/h ft^2 °F SI: W/m^2 K	Fiberglass/Vinyl I-P: Btu/h ft^2 °F SI: W/m^2 K
Single glazing with uncoated ⅛ in. [3.2 mm] clear pane	1.23 (7.01)	1.07 (6.08)	0.91 (5.20)	0.85 (4.83)
Single glazing with uncoated ¼ in. [6.4 mm] acrylic/polycarbonate pane	1.10 (6.23)	0.94 (5.35)	0.80 (4.52)	0.74 (4.18)
Double glazing with ⅛ in. [3.2 mm] panes: uncoated clear | clear with ¼ in. [6.4 mm] air space	0.81 (4.62)	0.64 (3.61)	0.55 (3.14)	0.50 (2.84)
Double glazing with ⅛ in. [3.2 mm] panes: uncoated clear | clear with ½ in. [13 mm] air space	0.76 (4.30)	0.58 (3.31)	0.50 (2.86)	0.45 (2.58)
Double glazing with ⅛ in. [3.2 mm] panes: uncoated clear | low-e (0.2) on surface[b] 3 with ½ in. [13 mm] air space	0.65 (3.70)	0.48 (2.75)	0.41 (2.34)	0.37 (2.07)
Triple glazing with ⅛ in. [3.2 mm] panes: uncoated clear | clear with ½ in. [13 mm] air spaces	0.61 (3.46)	0.44 (2.47)	0.38 (2.14)	0.34 (1.90)
Triple glazing with ⅛ in. [3.2 mm] panes: uncoated clear | low-e (0.2) on surfaces[b] 3 and 5 with ½ in. [13 mm] air spaces	0.52 (2.95)	0.35 (1.99)	0.30 (1.69)	0.26 (1.48)
Quadruple glazing with ⅛ in. [3.2 mm] panes: uncoated clear | low-e (0.1) on surfaces[b] 3 and 5 with ½ in. [13 mm] air spaces	0.48 (2.71)	0.31 (1.77)	0.26 (1.49)	0.23 (1.28)

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]Based upon an operable 3-ft × 5-ft (0.9-m × 1.5-m) aluminum-framed window.

[b]Glazing surfaces are numbered starting with the surface closest to the sun; thus, surface 2 would be the inner surface of an exterior pane of glass.

TABLE E.15 Representative Window Characteristics[a]

Glazing Description and Reference Number	Layers of Glazing and Spaces (outside to inside)	Frame (and spacer)	*Total Window U-Factor* *I-P* Btu/h ft² °F	*SI* W/m²K	*Total Window Solar and Optical Properties* SHGC[b]	VT[c]	LSG[d]	FHR[e]	FCR[e]	*Air Leakage* *I-P* cfm/lin ft	*SI* L/s m	*I-P* cfm/ft²	*SI* L/s m²
1. Single-glazed clear	⅛ in. (3 mm) clear	Aluminum, no thermal break	1.30	7.38	0.79	0.69	0.87	0	0	0.65	1.01	0.98	4.98
2. Single-glazed bronze	⅛ in. (3 mm) bronze	Aluminum, no thermal break	1.30	7.38	0.69	0.52	0.75	–2	8	0.65	1.01	0.98	4.98
3. Double-glazed clear	⅛ in. (3 mm) clear ½ in. (13 mm) air ⅛ in. (3 mm) clear	Aluminum, thermal break (aluminum)	0.64	3.63	0.65	0.62	0.95	19	12	0.37	0.57	0.56	2.85
4. Double-glazed bronze	⅛ in. (3 mm) bronze ½ in. (13 mm) air ⅛ in. (3 mm) clear	Aluminum, thermal break (aluminum)	0.64	3.63	0.55	0.47	0.85	17	20	0.37	0.57	0.56	2.85
5. Double-glazed clear	⅛ in. (3 mm) clear ½ in. (13 mm) air ⅛ in. (3 mm) clear	Wood or vinyl (aluminum)	0.49	2.78	0.58	0.57	0.98	24	18	0.37	0.57	0.56	2.85
6. Double-glazed bronze	⅛ in. (3 mm) bronze ½ in. (13 mm) air ⅛ in. (3 mm) clear	Wood or vinyl (aluminum)	0.49	2.78	0.48	0.43	0.90	22	25	0.37	0.57	0.56	2.85
7. Double-glazed low-ε[f]	⅛ in. (3 mm) clear ½ in. (13 mm) argon ⅛ in. (3 mm) low-ε 0.20	Wood or vinyl (stainless)	0.33	1.87	0.55	0.52	0.95	32	19	0.10	0.16	0.15	0.76
8. Double-glazed low-ε[f]	⅛ in. (3 mm) low-ε 0.08 ½ in. (13 mm) argon ⅛ in. (3 mm) clear	Wood or vinyl (stainless)	0.30	1.70	0.44	0.56	1.27	32	27	0.10	0.16	0.15	0.76
9. Double-glazed spectrally selective[f]	⅛ in. (3 mm) low-ε 0.04 ½ in. (13 mm) argon ⅛ in. (3 mm) clear	Wood or vinyl (stainless)	0.29	1.65	0.31	0.51	1.65	30	36	0.10	0.16	0.15	0.76

10. Double-glazed spectrally selective[f]	⅛ in. (3 mm) low-ε 0.10 ½ in. (13 mm) argon ⅛ in. (3 mm) clear	Wood or vinyl (stainless)	0.31	1.76	0.26	0.31	1.19	27	40	0.10	0.16	0.15	0.76
11. Triple-glazed low-ε[f] superwindow	⅛ in. (3 mm) low-ε 0.08 ½ in. (13 mm) krypton ⅛ in. (3 mm) clear ½ in. (13 mm) krypton ⅛ in. (3 mm) low-ε 0.08	Insulated vinyl (insulated)	0.15	0.85	0.37	0.48	1.30	38	33	0.05	0.08	0.08	0.41
12. Triple-glazed clear	⅛ in. (3 mm) clear ½ in. (13 mm) air ⅛ in. (3 mm) clear ½ in. (13 mm) air ⅛ in. (3 mm) clear	Wood or vinyl (stainless)	0.34	1.93	0.52	0.53	1.02	32	22	0.10	0.16	0.15	0.76

Source: Residential Windows: A Guide to New Technologies and Energy Performance, by John Carmody, Stephen Selkowitz, and Lisa Heschong. © 1996 by John Carmody, Stephen Selkowitz, and Lisa Heschong. Adapted by permission of W. W. Norton & Company, New York. (SI units appended by the authors.)

[a]Based upon a casement window, 2 ft × 4 ft (610 mm × 1220 mm).

[b]Solar heat gain coefficient (higher numbers mean more solar heat flow).

[c]Visible transmittance (higher numbers mean more light transmitted).

[d]Light-to-solar gain ratio, LSG = VT/SHGC. For typical center-of-glass values for VT and SHGC, see Table E.18.

[e]FHR (fenestration heating rating) and FCR (fenestration cooling rating) are heating season and cooling season (respectively) estimates of the percentage of energy saved in a typical residential application compared to using window 1.

[f]Low-ε ratings indicate what percentage of the long-wavelength radiant energy is admitted; 0.20 therefore admits 20% and reflects 80%.

TABLE E.16 Representative Skylight U-Factors[a]

Part A. I-P Units (Btu/h ft² °F)

Glazing	Manufactured Skylight[b] Aluminum, Thermal Break No	Aluminum, Thermal Break Yes	Reinforced Vinyl/ Aluminum-Clad Wood	Wood/ Vinyl	Site-Assembled Glazing[c] Aluminum, Thermal Break No	Aluminum, Thermal Break Yes	Structural Glazing
Single glazed	1.98	1.89	1.75	1.47	1.36	1.25	1.25
Double glazed, ½-in. gap	1.30	1.10	1.04	0.84	0.81	0.69	0.65
Double glazed, ½-in. gap, argon low-ε 0.20 on surface[d] 2 or 3	1.15	0.95	0.89	0.68	0.66	0.55	0.51
Double glazed, ½-in. gap, argon low-ε 0.10 on surface[d] 2 or 3	1.13	0.93	0.87	0.67	0.65	0.53	0.49
Double glazed, ½-in. gap, low-ε 0.05 on surface[d] 2 or 3	1.11	0.91	0.85	0.65	0.63	0.52	0.47
Triple glazed, ½-in. gaps	1.10	0.87	0.81	0.61	0.62	0.51	0.45
Triple glazed, ½-in. gaps, argon low-ε 0.10 on surfaces[d] 2 or 3 and 4 or 5	0.95	0.72	0.67	0.47	0.48	0.37	0.31

Part B. SI Units (W/m² K)

Glazing	Manufactured Skylight[b] Aluminum, Thermal Break No	Aluminum, Thermal Break Yes	Reinforced Vinyl/ Aluminum-Clad Wood	Wood/ Vinyl	Site-Assembled Glazing[c] Aluminum, Thermal Break No	Aluminum, Thermal Break Yes	Structural Glazing
Single glazed	11.24	10.73	9.94	8.35	7.72	7.10	7.10
Double glazed, 12.7 mm gap	7.38	6.25	5.91	4.77	4.60	3.92	3.69
Double glazed, 12.7 mm gap, argon, low-ε 0.20 on surface[d] 2 or 3	6.53	5.39	5.05	3.86	3.75	3.12	2.90
Double glazed, 12.7 mm gap, argon, low-ε 0.10 on surface[d] 2 or 3	6.42	5.28	4.94	3.80	3.69	3.01	2.78
Double glazed, 12.7 mm gap, low-ε 0.05 on surface[d] 2 or 3	6.30	5.17	4.83	3.69	3.58	2.95	2.67
Triple glazed, 12.7 mm gaps	6.25	4.94	4.60	3.46	3.52	2.90	2.56
Triple glazed, 12.7-mm gaps, argon, low-ε 0.10 on surfaces[d] 2 or 3 and 4 or 5	5.39	4.09	3.80	2.67	2.73	2.10	1.76

Source: Excerpted with permission; ©ASHRAE, ANSI/ASHRAE Standard 90.1-2013: *Energy Standard for Buildings Except Low-Rise Residential Buildings*. The SI values were appended to ASHRAE's I-P data by the authors.

[a]All glazings are ⅛-in. (3-mm) thickness. Winter conditions, 15-mph (24-km/h) wind with 0°F (–18°C) outside, 70°F (21°C) inside, no solar radiation. Glazing is sloped at 20° from the horizontal.

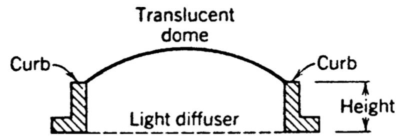
[b]Skylight is 2 ft × 4 ft (600 mm × 1200 mm) with frame width as follows: aluminum (with or without thermal break), 0.7 in. (18 mm); wood/vinyl/aluminum-clad, 0.9 in. (23 mm); structural glazing, not applicable.

[c]Site-assembled glazing size is 4 ft × 4 ft (1200 mm × 1200 mm) with aluminum frame width of 2.25 in. (57 mm), structural glazing width of 2.5 in. (64 mm).

[d]Glazing layer surfaces are numbered from outside to inside.

TABLE E.17 Solar Heat Gain Coefficients (SHGC) for Plastic Domed Horizontal Skylights

		Curb (See Sketch Below)			
Dome	**Light Diffuser (Translucent)**	**Height, in. (mm)**	**Width-to-Height Ratio**	**Solar Heat Gain Coefficient**	**U-Factor at Center of Skylight[b]**
Clear ($\tau = 0.86$[a])	Yes ($\tau = 0.58$)	0 (0)	∞	0.53	0.46 (2.6)
		9 (230)	5	0.50	0.43 (2.4)
		18 (460)	2.5	0.44	0.40 (2.3)
Clear ($\tau = 0.86$)	None	0 (0)	∞	0.86	0.80 (4.5)
		9 (230)	5	0.77	0.75 (4.3)
		18 (460)	2.5	0.70	0.70 (4.0)
Translucent ($\tau = 0.52$)	None	0 (0)	∞	0.50	0.80 (4.5)
		18 (460)	2.5	0.40	0.70 (4.0)
Translucent ($\tau = 0.27$)	None	0 (0)	∞	0.30	0.80 (4.5)
		9 (230)	5	0.26	0.75 (4.3)
		18 (460)	2.5	0.24	0.70 (4.0)



Source: Excerpted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a] τ refers to the transmittance of the dome or diffusing element, as noted.

[b] U-factor units: Btu/h ft^2 °F (W/m^2 K).

TABLE E.18 Solar Optical Properties of Representative Glazings and Window Assemblies

Glazing System Description	Center of Glazing VT	Center of Glazing SHGC[a]	Window Assembly VT[a,b]	Window Assembly SHGC[a,b]
Single Glazings—with ¼ in. (6.4 mm) panes except as noted				
Uncoated ⅛ in. [3.2 mm] clear	0.90	0.86	0.80	0.78
Uncoated clear	0.88	0.81	0.78	0.74
Uncoated bronze	0.54	0.62	0.48	0.57
Uncoated green	0.76	0.60	0.68	0.55
Uncoated gray	0.46	0.59	0.41	0.54
Reflective stainless steel on clear (8%)	0.08	0.19	0.07	0.18
Reflective stainless steel on clear (20%)	0.20	0.31	0.18	0.29
Double Glazings—all with ¼ in. (6.4 mm) panes				
Uncoated clear | clear	0.78	0.70	0.69	0.64
Uncoated bronze | clear	0.47	0.49	0.42	0.45
Uncoated high-performance green | clear	0.59	0.39	0.53	0.36
Reflective stainless steel on clear (8%) | clear	0.07	0.13	0.06	0.13
Reflective titanium on clear (20%) | clear	0.18	0.21	0.16	0.21
Clear | low-e (0.2) on surface[c] 3	0.73	0.65	0.65	0.59
Low-e (0.2) on surface 2 | clear	0.73	0.60	0.64	0.55
Low-e (0.1) on surface 2 | clear	0.72	0.60	0.64	0.55
Low-e (0.05) on surface 2 | clear	0.70	0.37	0.62	0.34
Triple Glazings—all with ¼ in. (6.4 mm) panes				
Clear | clear | clear	0.70	0.61	0.62	0.56
High-performance green | clear | clear	0.53	0.32	0.47	0.30
Low-e (0.2) on surface 2 | clear | clear	0.64	0.53	0.57	0.51
Low-e (0.1) on surface 2 | clear | low-e (0.1) on surface 5	0.59	0.36	0.53	0.34
Low-e (0.05) on surface 2 | low-e (0.05) on surface 4 | clear	0.55	0.26	0.49	0.25

Source: Excerpted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]Values are for a normal angle of solar incidence, see the 2013 *ASHRAE Handbook—Fundamentals* for SHGC values at other incidence angles.

[b]Based upon an operable 3-ft × 5-ft (0.9-m × 1.5-m) aluminum-framed window.

[c]Glazing surfaces are numbered starting with the surface closest to the sun; thus, surface 2 would be the inner surface of an exterior pane of glass.

TABLE E.19 Solar Optical Properties of Transparent Plastics

	Transmittance		
Type of Plastic	**Visible**	**Solar**	**SC[a]**
Acrylic			
Clear	0.92	0.85	0.98
Gray tint	0.16	0.27	0.52
Gray tint	0.33	0.41	0.63
Gray tint	0.45	0.55	0.74
Gray tint	0.59	0.62	0.80
Gray tint	0.76	0.74	0.89
Bronze tint	0.27	0.35	0.58
Bronze tint	0.49	0.56	0.75
Bronze tint	0.61	0.62	0.80
Bronze tint	0.75	0.75	0.90
Reflective[b]	0.14	0.12	0.21
Polycarbonate			
Clear, ⅛ in. (3 mm)	0.88	0.82	0.98
Gray or bronze, ⅛ in. (3 mm)	0.50	0.57	0.74

Source: Previously adapted, with the permission of ASHRAE, from the *1997 ASHRAE Handbook—Fundamentals.* This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

[a]Shading coefficient; multiply SC by 0.87 for an approximate estimation of SHGC (solar heat gain coefficient).

[b]Aluminum metalized polyester film on plastic.

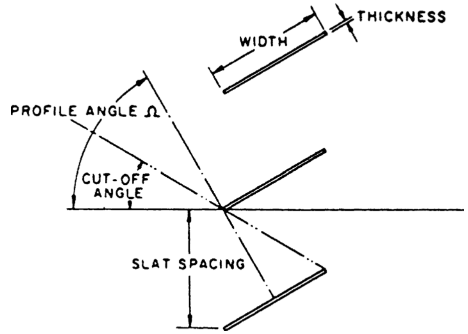
TABLE E.20 Approximate Shading Coefficients (SC) of External Shading Devices

Awnings	
Of venetian blind type, ⅔ drawn	0.43
Of venetian blind type, fully drawn	0.15
Dark or medium canvas	0.25
Shading screens	0.28–0.23
Louvers, movable	0.15–0.10
Overhang: continuous, completely shading window	0.25
Dense tree casting heavy shade	0.25

Source: Adapted from V. Olgyay, *Design with Climate*. 1963. Princeton University Press, Princeton, NJ.

TABLE E.21 Shading Coefficients (SC) for Louvered Sunscreens

Profile Angle, (deg)	*Group 1*[a]		*Group 2*[b]		*Group 3*[c]		*Group 4*[d]		*Group 5*[e]		*Group 6*[f]	
	Transmittance	SC	Transmittance	SC	Transmittance	SC	Transmittance	SC	Transmittance	SC	Transmittance	SC
10	0.23	0.35	0.25	0.33	0.40	0.51	0.48	0.59	0.15	0.27	0.26	0.45
20	0.06	0.17	0.14	0.23	0.32	0.42	0.39	0.50	0.04	0.11	0.20	0.35
30	0.04	0.15	0.12	0.21	0.21	0.31	0.28	0.38	0.03	0.10	0.13	0.26
≥40	0.04	0.15	0.11	0.20	0.07	0.18	0.20	0.30	0.03	0.10	0.04	0.13



Source: Previously adapted, with the permission of ASHRAE, from the 1997 *ASHRAE Handbook—Fundamentals*. This citation to an older version of the Handbook is intentional and provides access to historic reference information of ongoing interest.

Note: The 2001 *ASHRAE Handbook—Fundamentals* presents a different and more complex methodology for determining solar gain through externally shaded glazing systems—involving the variables F_u (unshaded fraction of glazing) and EAC (exterior solar attenuation coefficient). The methodology and associated data are not presented here, as they are less intuitive and less suited to hand calculations than the older SC data presented in this table. Refer to the 2001 *Handbook* for this new information.

[a]Group 1: Black, width over spacing ratio 1.15/1; 23 louvers/in. (1.1 mm between louvers), with ¼-in. (6.4-mm) single clear glass.

[b]Group 2: Light color; high reflectance, otherwise same as group 1.

[c]Group 3: Black or dark color; width over spacing ratio 0.85/1; 17 louvers/in. (1.5 mm between louvers), with ¼-in. (6.4-mm) single clear glass.

[d]Group 4: Light color or unpainted aluminum; high reflectance; otherwise same as group 3.

[e]Group 5: Same as group 1, except two lights of ¼-in. (6.4-mm) clear glass with ½-in. (12.7-mm) air space.

[f]Group 6: Same as group 3, except two lights of ¼-in. (6.4-mm) clear glass with ½-in. (12.7-mm) air space.

TABLE E.22 Performance Characteristics of Adjustable Sunshading

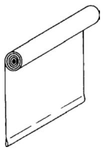
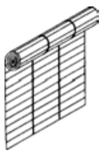
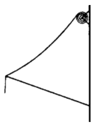
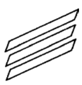
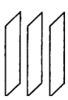
Shading Type	Typical Orientations	Solar Heat Rejection	Daylight Distribution	Ventilation	View	Winter Night Insulation
Roll-down Shades **Solid** 	East and west, where it is rolled down daily during hours of direct sun exposure.	Blocks direct, diffuse, and reflected radiation. Heat builds up between shade and glass unless vented.	Translucent shades diffuse light evenly but may become a source of glare due to brightness. If shades are colored, incoming light will be colored.	Blocks ventilation airflow.	Blocks view.	Can be effective if airflow around the shade is blocked (providing dead air space).
Slatted 	East and west, where it is rolled down daily during hours of direct sun exposure.	Blocks most direct, diffuse, and reflected radiation. Heat can convect through slats into space.	A thinly striped pattern of direct sun is admitted. Opaque slats will heavily filter daylight.	Greatly reduces ventilation airflow.	Substantially obstructs and filters view.	No value unless slats can be fitted together to close openings and trap air between shade and glass.
Fold-out Retractable Awning 	Any orientation. On south, awnings can be deep and be left in position for weeks at a time.	Blocks direct sun; admits most diffuse and reflected radiation. Heat collected on awning easily dissipated outside of building.	Translucent awnings evenly diffuse sunlight. (Colored awnings will color light.) Awnings can redirect ground-reflected light into building for distribution by ceiling.	Blocks view of sky; permits view of ground and some surroundings (depending upon positioning).	Reduces ventilation airflow somewhat, tends to direct wind upward into space.	If awning folds back against window, it can provide some insulation value—but likely limited.
Pivoting Louvers **Horizontal** 	South; also used on other elevations (although less effective).	Blocks direct sun; admits ground-reflected and some diffuse radiation.	Skylight can be reflected to ceiling plane for distribution into building. Ground-reflected light can be reflected into space.	Reduces ventilation airflow somewhat (based upon louver spacing); directs wind upward into space.	Blocks sky view; filters ground and surrounding views (depending upon angle of louvers).	Closed louvers can provide some insulation value (depending upon tightness of closure).
Vertical 	East and west; also used on north. Not as effective on south as horizontal louvers.	Blocks direct sun; admits most ground-reflected and diffuse radiation.	Blocks direct sunlight; admits most ground-reflected and diffuse light.	Reduces ventilation airflow somewhat (to extent of solidity); directs wind sideways into space.	Filters view, especially to sides.	Closed louvers can provide some insulation value (depending upon tightness of closure).

TABLE E.23 Shading Coefficients (SC) for Glazing with Integral or Interior Shading

Part A. SC for Insulating Glass[a] with Indoor Shading by Venetian Blinds or Roller Shades

				Type of Shading				
						Roller Shade		
		Solar Transmittance[b]		*Venetian Blinds*[c]		*Opaque*		*Translucent*
Type of Glass	Nominal Thickness, Each Light	Outer Pane	Inner Pane	Medium	Light	Dark	White	Light
Clear out	⅛ in. (3.2 mm)	0.87	0.87	0.62	0.58 (45° open)	0.71	0.35	0.40
Clear in				0.63	0.58 (closed)[d]			
Heat-absorbing[e] out	¼ in. (6.4 mm)	0.46	0.80	0.39	0.36	0.40	0.22	0.30
Clear in								
Reflective coated glass								
SC[f] = 0.20				0.19	0.18			
0.30				0.27	0.26			
0.40				0.34	0.33			

Part B. Shading Coefficients for Double Glazing with Between-Glass Shading

		Solar Transmittance[b]			*Type of Shading*		
					Venetian Blinds		
Type of Glass	Nominal Thickness, Each Pane	Outer Pane	Inner Pane	Description of Air Space	Light	Medium	Louvered Sun Screen
Clear out	⅛ in. (3.2 mm)	0.87	0.87	Shade in contact with glass or shade separated from glass by airspace	0.33	0.36	0.43
Clear in							
Clear out	¼ in. (6.4 mm)	0.80	0.80	Shade in contact with glass; voids filled with plastic	—	—	0.49
Clear in							

Heat-absorbing[e] out Clear in	¼ in. (6 mm)	0.46	0.80	Shade in contact with glass or shade separated from glass by airspace	0.28	0.30	0.37
				Shade in contact with glass; voids filled with plastic	—	—	0.41

Source: Previously adapted, with the permission of ASHRAE, from the 1997 *ASHRAE Handbook—Fundamentals*. This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

Note: The 2001 *ASHRAE Handbook—Fundamentals* presents a different and more complex methodology for determining solar gain through internally and integrally shaded glazing systems—involving the variables IAC and BAC (interior and between-glass solar attenuation coefficients, respectively). The methodology and associated data are not presented here, as they are less intuitive and less suited to hand calculations than the older SC data presented in this table. Refer to the 2001 *Handbook* for this new information.

[a]Factory-manufactured units with 3⁄16-in. (4.8-mm), ¼-in. (6.4-mm), or ½-in. (12.7-mm) air space.

[b]Refer to manufacturers' literature for exact values.

[c]For vertical blinds with opaque, white, or beige louvers, tightly closed, SC is approximately the same as for opaque white roller shades.

[d]Use these values only when operation is automated for solar gain reduction (as opposed to daylight use).

[e]Refers to bronze or green-tinted, heat-absorbing glass.

[f]SC for glass with no shading device.

TABLE E.24 Shading Coefficients (SC) for Single and Insulating Glass with Draperies

			Range of Shading Coefficients	
			Drapery Fabrics[b]	
Glazing	**Glass Trans.**	**Glass SC[a]**	**High Transmittance, Low Reflectance[c]**	**Low Transmittance, High Reflectance[c]**
Single Glass				
⅛ in. (3.2 mm) clear	0.86	1.00	0.87	0.37
¼ in. (6.4 mm) clear	0.80	0.95	0.80	0.35
½ in. (12.7 mm) clear	0.71	0.88	0.74	0.35
¼ in. (6.4 mm) heat absorbing	0.46	0.67	0.57	0.33
½ in. (12.7 mm) heat absorbing	0.24	0.50	0.43	0.30
Reflective coated (see manufacturers' literature for exact values)	—	0.60	0.57	0.33
	—	0.50	0.46	0.31
	—	0.40	0.36	0.26
	—	0.30	0.25	0.20
Insulating Glass, ½ in. (12.7 mm) air space				
Clear out and clear in	0.64	0.83	0.66	0.35
Heat absorbing out and clear in	0.37	0.55	0.49	0.32
Reflective coated (see manufacturers' literature for exact values)	—	0.40	0.38	0.28
	—	0.30	0.29	0.24
	—	0.20	0.19	0.15

Source: Previously adapted, with the permission of ASHRAE, from the 1997 *ASHRAE Handbook—Fundamentals*. This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

Note: The 2001 *ASHRAE Handbook—Fundamentals* presents a different and more complex methodology for determining solar gain through internally shaded glazing systems—involving the variable IAC (interior solar attenuation coefficient). The methodology and associated data are not presented here, as they are less intuitive and less suited to hand calculations than the older SC data presented in this table. Refer to the 2001 *Handbook* for this new information.

[a]For glass alone, with no drapery.

[b]Draperies of 100% fullness, loose hanging.

[c]See the 1997 *ASHRAE Handbook—Fundamentals*, Chapter 27, Table 29, for more detailed listings.

APPENDIX F

Ventilation and Infiltration

This appendix provides data to support the design and analysis process presented in Chapters 9, 10, and 11.

- TABLE F.1 Minimum Ventilation Rates in Breathing Zone (for Buildings Except Low-Rise Residential)
- TABLE F.2 Recommended Ventilation and Exhaust Air Requirements—Low-Rise Residential
- TABLE F.3 Estimated Overall Infiltration Rates for Small Buildings
- TABLE F.4 Approximate Infiltration through Doors and Windows of Small Buildings

TABLE F.1 Minimum Ventilation Rates in Breathing Zone (for Buildings Except Low-Rise Residential)

	People Outdoor Air Rate		*Area Outdoor Air Rate*			*Default Values*		
	R_P		R_A		*Notes*	*Occupant Density*	*Combined Outdoor Air Rate*	
Occupancy Category	**I-P: cfm/Person**	**SI: L/s Person**	**I-P: cfm/ft^2**	**SI: L/s m^2**		**#/1000 ft^2 (#/100 m^2)**	**I-P: cfm/Person**	**SI: L/s Person**
Correctional Facilities								
Cell	5	2.5	0.12	0.6		25 (26.9)	10	4.9
Day room	5	2.5	0.06	0.3		30 (32.3)	7	3.5
Guard stations	5	2.5	0.06	0.3		15 (16.1)	9	4.5
Booking/waiting	7.5	3.8	0.06	0.3		50 (53.8)	9	4.4
Educational Facilities								
Daycare (through age 4)	10	5	0.18	0.9		25 (26.9)	17	8.6
Classrooms (ages 5–8)	10	5	0.12	0.6		25 (26.9)	15	7.4
Classrooms (age 9 plus)	10	5	0.12	0.6		35 (37.7)	13	6.7
Lecture classroom	7.5	3.8	0.06	0.3		65 (70.0)	8	4.3
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3		150 (161)	8	4.0
Art classroom	10	5	0.18	0.9		20 (21.5)	19	9.5
Science laboratories	10	5	0.18	0.9		25 (26.9)	17	8.6
Wood/metal shop	10	5	0.18	0.9		20 (21.5)	19	9.5
Computer lab	10	5	0.12	0.6		25 (26.9)	15	7.4
Media center	10	5	0.12	0.6	A	25 (26.9)	15	7.4
Music/theater/dance	10	5	0.06	0.3		35 (37.7)	12	5.9
Multi-use assembly	7.5	3.8	0.06	0.3		100 (108)	8	4.1
Food and Beverage Service								
Restaurant dining rooms	7.5	3.8	0.18	0.9		70 (75.3)	10	5.1
Cafeteria/fast food dining	7.5	3.8	0.18	0.9		100 (108)	9	4.7
Bars, cocktail lounges	7.5	3.8	0.18	0.9		100 (108)	9	4.7
General								
Conference/meeting	5	2.5	0.06	0.3		50 (53.8)	6	3.1
Corridors	—	—	0.06	0.3		—		
Storage rooms	—	—	0.12	0.6	B	—		
Hotels, Motels, Resorts, Dormitories								
Bedroom/living room	5	2.5	0.06	0.3		10 (10.8)	11	5.5
Barracks sleeping areas	5	2.5	0.06	0.3		20 (21.5)	8	4

Lobbies/prefunction	7.5	3.8	0.06	0.3		30 (32.3)	10	4.8
Multi-purpose assembly	5	2.5	0.06	0.3		120 (129)	6	2.8
Office Buildings								
Office space	5	2.5	0.06	0.3		5 (5.4)	17	8.5
Reception areas	5	2.5	0.06	0.3		30 (32.3)	7	3.5
Telephone/data entry	5	2.5	0.06	0.3		60 (64.6)	6	3
Main entry lobbies	5	2.5	0.06	0.3		10 (10.8)	11	5.5
Miscellaneous Spaces								
Bank vaults/safe deposit	5	2.5	0.06	0.3		5 (5.4)	17	8.5
Computer (not printing)	5	2.5	0.06	0.3		4 (4.3)	20	10
Pharmacy (prep. area)	5	2.5	0.18	0.9		10 (10.8)	23	11.5
Photo studios	5	2.5	0.12	0.6		10 (10.8)	17	8.5
Shipping/receiving	10	5	0.12	0.6	B	2	70	
Transportation waiting	7.5	3.8	0.06	0.3		100 (108)	8	4.1
Warehouses	10	5	0.06	0.3	B	—		
Public Assembly Spaces								
Auditorium seating area	5.0	2.5	0.06	0.3		150 (161)	5	2.7
Places of religious worship	5.0	2.5	0.06	0.3		120 (129)	6	2.8
Courtrooms	5.0	2.5	0.06	0.3		70 (75.3)	6	2.9
Legislative chambers	5.0	2.5	0.06	0.3		50 (53.8)	6	3.1
Libraries	5.0	2.5	0.12	0.6		10 (10.8)	17	8.5
Lobbies	5.0	2.5	0.06	0.3		150 (161)	5	2.7
Museums (children's)	7.5	3.8	0.12	0.6		40 (43.0)	11	5.3
Museums/galleries	7.5	3.8	0.06	0.3		40 (43.0)	9	4.6
Retail								
Sales (except as below)	7.5	3.8	0.12	0.6		15 (16.1)	16	7.8
Mall common areas	7.5	3.8	0.06	0.3		40 (43.0)	9	4.6
Barber shop	7.5	3.8	0.06	0.3		25 (26.9)	10	5
Beauty and nail salons	20	10	0.12	0.6		25 (26.9)	25	12.4
Pet shops (animal areas)	7.5	3.8	0.18	0.9		10 (10.8)	26	12.8
Supermarket	7.5	3.8	0.06	0.3		8 (8.6)	15	7.6
Coin-operated laundries	7.5	3.8	0.06	0.3		20 (21.5)	11	5.3

TABLE F.1 Minimum Ventilation Rates in Breathing Zone (for Buildings Except Low-Rise Residential) (*Continued*)

	People Outdoor Air Rate		***Area Outdoor Air Rate***		***Default Values***			
	R_P		R_A		***Notes***	***Occupant Density***	***Combined Outdoor Air Rate***	
Occupancy Category	**I-P: cfm/Person**	**SI: L/s Person**	**I-P: cfm/ft²**	**SI: L/s m²**		**#/1000 ft² (#/100 m²)**	**I-P: cfm/Person**	**SI: L/s Person**
Sports and Entertainment								
Sports arena (play area)	—	—	0.3	1.5		—		
Gym, stadium (play area)	—	—	0.3	1.5		30 (32.3)		
Spectator areas	7.5	3.8	0.06	0.3		150 (161)	8	4
Swimming (pool and deck)	—	—	0.48	2.4	C	—		
Disco/dance floors	20	10	0.06	0.3		100 (108)	21	10.3
Health club/aerobics room	20	10	0.06	0.3		40 (43.0)	22	10.8
Health club/weight rooms	20	10	0.06	0.3		10 (10.8)	26	13
Bowling alley (seating)	10	5	0.12	0.6		40 (43.0)	13	6.5
Gambling casinos	7.5	3.8	0.18	0.9		120 (129)	9	4.6
Game arcades	7.5	3.8	0.18	0.9		20 (21.5)	17	8.3
Stages, studios	10	5	0.06	0.3	D	70 (75.3)	11	5.4

Source: Reprinted with permission; ASHRAE, *Addendum n* to ANSI/ASHRAE Standard 62.1-2013, *Ventilation for Acceptable Indoor Air Quality*. SI conversions for population density added by the authors of this book (not part of original source).

General Notes

1. *Related Requirements:* The rates in this table are based on all other requirements of Standard 62-2001 (with addenda) being met.
2. *Smoking:* This table applies to no-smoking areas. Rates for smoking-permitted spaces must be determined using other means.
3. *Air Density:* Volumetric airflow rates are based on an air density of 1.2 kg_{da}/m^3 (0.075 lb_{da}/ft^3), which corresponds to dry air at a barometric pressure of 101.3 kPa (1 atm) and an air temperature of 21°C (70°F). Rates may be adjusted for actual density, but such adjustment is not required for compliance with this standard.
4. *Default Occupant Density:* The default occupant density shall be used when actual occupant density is not known.
5. *Default Combined Outdoor Air Rate (per person):* This rate is based on the default occupant density.
6. *Unlisted Occupancies:* If the occupancy category for a proposed space or zone is not listed, the requirements for the listed occupancy category that is most similar in terms of occupant density, activities, and building construction shall be used.
7. *Residential Facilities, Health Care Facilities, and Vehicles:* Rates shall be determined in accordance with Appendix E (of Standard 62-2001).

Item-Specific Notes:

A. For high school and college libraries, use values shown for Public Spaces—Libraries.
B. Rate may not be sufficient when stored materials include those having potentially harmful emissions.
C. Rate does not allow for humidity control. Additional ventilation or dehumidification may be required to remove moisture.
D. Rate does not include special exhaust for stage effects, e.g., dry ice vapors, smoke.

TABLE F.2 Recommended Ventilation and Exhaust Air Requirements—Low-Rise Residential

Part A: Ventilation Air cfm (L/s)					
Floor Area ft^2 (m^2)	1 Bedroom	2 Bedrooms	3 Bedrooms	4 Bedrooms	5 Bedrooms
<500 (<47)	30 (14)	38 (18)	45 (21)	53 (25)	60 (28)
501–1000 (47–93)	45 (21)	53 (24)	60 (28)	68 (31)	75 (35)
1001–1500 (93–139)	60 (28)	68 (31)	75 (35)	83 (38)	90 (42)
1501–2000 (140–186)	75 (35)	83 (38)	90 (42)	98 (45)	105 (49)
2001–2500 (186–232)	90 (42)	98 (45)	105 (49)	113 (52)	120 (56)
2501–3000 (232–279)	105 (50)	113 (52)	120 (56)	128 (59)	135 (63)
3001–3500 (279–325)	120 (56)	128 (59)	135 (63)	143 (66)	150 (70)
3501–4000 (325–372)	135 (63)	143 (66)	150 (70)	158 (73)	165 (77)
4001–4500 (372–418)	150 (70)	158 (73)	165 (77)	173 (80)	180 (84)
4501–5000 (418–465)	165 (77)	173 (80)	180 (84)	188 (87)	195 (91)
Part B: Exhaust Air					
If *continuous*—local ventilation exhaust air flow rates:					
Kitchen: 5 air changes per hour (based upon kitchen volume)					
Bathroom: 20 cfm [10 L/s]					
If *intermittent*—local ventilation exhaust air flow rates:					
Kitchen: 100 cfm (50 L/s) (vented range hood required if exhaust fan flow rate is less than 5 kitchen air changes per hour)					
Bathroom: 50 cfm (25 L/s)					

Source: Reprinted with permission; ©ASHRAE, ANSI/ASHRAE Standard 62.2-2013, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. See Standard 62.2 for definitions, assumptions, implementation, and exceptions.

TABLE F.3 Estimated Overall Infiltration Rates for Small Buildings

Part A. Construction Types

Construction Type	Description
Tight	Good multifamily residential construction with close-fitting doors, windows, and framing is considered tight. New houses with full vapor retarder, no fireplace, well-fitted windows, weather-stripped doors, one-story, and less than 1500 ft^2 (140 m^2) floor area fall into this category.
Medium	Medium structures include new two-story frame houses or one-story houses more than 10 years old with average maintenance, a floor area greater than 1500 ft^2 (140 m^2), average-fit windows and doors, and a fireplace with damper and glass closure. Below-average multifamily construction falls in this category.
Loose	Loose structures are poorly constructed single and multifamily residences with poorly fitted windows and doors. Examples include houses more than 20 years old, of average maintenance, having a fireplace without damper or glass closure, or having more than an average number of vented appliances. Average manufactured homes are in this category.

Part B. Design Infiltration Rate (ACH) for Winter: Indoors 68ºF (20ºC); Wind Speed = 15 mph (6.7 m/s)

Construction Type	*Winter Outdoor Design Temperature*									
	ºF: 50	**40**	**30**	**20**	**10**	**0**	**–10**	**–20**	**–30**	**–40**
	ºC: 10	**4**	**–1**	**–7**	**–12**	**–18**	**–23**	**–29**	**–34**	**–40**
Tight	0.41	0.43	0.45	0.47	0.49	0.51	0.53	0.55	0.57	0.59
Medium	0.69	0.73	0.77	0.81	0.85	0.89	0.93	0.97	1.00	1.05
Loose	1.11	1.15	1.20	1.23	1.27	1.30	1.35	1.40	1.43	1.47

Part C. Design Infiltration Rate (ACH) for Summer: Indoors 75ºF (24ºC); Wind Speed = 7.5 mph (3.4 m/s)

Construction Type	*Summer Outdoor Design Temperature*					
	ºF: 85	**90**	**95**	**100**	**105**	**110**
	ºC: 29	**32**	**35**	**38**	**41**	**43**
Tight	0.33	0.34	0.35	0.36	0.37	0.38
Medium	0.46	0.48	0.50	0.52	0.54	0.56
Loose	0.68	0.70	0.72	0.74	0.76	0.78

Part D. Infiltration Rates per Unit Floor Area

Ceiling Height	Air Flow	*Air Changes per Hour*																	
		0.3	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2.0**
7.5 ft	cfm/ft^2	0.04	0.05	0.06	0.08	0.09	0.10	0.11	0.13	0.14	0.15	0.16	0.18	0.19	0.20	0.21	0.23	0.24	0.25
2.3 m	$L/s\ m^2$	0.20	0.25	0.31	0.41	0.46	0.51	0.56	0.66	0.71	0.76	0.81	0.91	0.97	1.02	1.07	1.17	1.22	1.27
8.0 ft	cfm/ft^2	0.04	0.05	0.07	0.08	0.09	0.11	0.12	0.13	0.15	0.16	0.17	0.19	0.20	0.21	0.23	0.24	0.26	0.27
2.4 m	$L/s\ m^2$	0.20	0.25	0.36	0.41	0.46	0.56	0.61	0.66	0.76	0.81	0.86	0.97	1.02	1.07	1.17	1.22	1.32	1.37
8.5 ft	cfm/ft^2	0.04	0.06	0.07	0.09	0.10	0.11	0.13	0.14	0.16	0.17	0.18	0.20	0.21	0.23	0.24	0.26	0.27	0.28
2.6 m	$L/s\ m^2$	0.20	0.31	0.36	0.46	0.51	0.56	0.66	0.71	0.81	0.86	0.91	1.02	1.07	1.17	1.22	1.32	1.37	1.42
9.0 ft	cfm/ft^2	0.05	0.06	0.08	0.09	0.11	0.12	0.14	0.15	0.17	0.18	0.20	0.21	0.23	0.24	0.26	0.27	0.29	0.30
2.7 m	$L/s\ m^2$	0.25	0.31	0.41	0.46	0.56	0.61	0.71	0.76	0.86	0.91	1.02	1.07	1.17	1.22	1.32	1.37	1.47	1.52

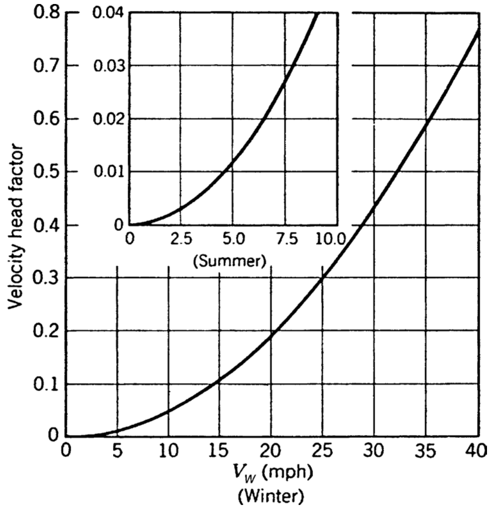
Part E. Infiltration Heat Flow Rates per Unit Floor Area

Ceiling Height	Heat Flow	*Air Changes per Hour*																	
		0.3	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**1.8**	**1.9**	**2.0**
7.5 ft	Btu/h ft^2 ºF	0.04	0.05	0.07	0.08	0.09	0.11	0.12	0.14	0.15	0.16	0.18	0.20	0.20	0.22	0.23	0.24	0.26	0.27
2.3 m	W/m^2 K	0.23	0.28	0.40	0.45	0.51	0.63	0.68	0.80	0.85	0.91	1.02	1.14	1.14	1.25	1.31	1.36	1.48	1.53
8.0 ft	Btu/h ft^2 ºF	0.04	0.06	0.07	0.09	0.10	0.12	0.13	0.14	0.16	0.17	0.19	0.22	0.22	0.23	0.24	0.26	0.27	0.29
2.4 m	W/m^2 K	0.23	0.34	0.40	0.51	0.57	0.68	0.74	0.80	0.91	0.97	1.08	1.25	1.25	1.31	1.36	1.48	1.53	1.65
8.5 ft	Btu/h ft^2 ºF	0.05	0.06	0.08	0.09	0.11	0.12	0.14	0.15	0.17	0.18	0.20	0.23	0.23	0.24	0.26	0.28	0.29	0.30
2.4 m	W/m^2 K	0.28	0.34	0.45	0.51	0.63	0.68	0.80	0.85	0.97	1.02	1.14	1.31	1.31	1.36	1.48	1.59	1.65	1.70
9.0 ft	Btu/h ft^2 ºF	0.05	0.06	0.08	0.10	0.11	0.13	0.15	0.16	0.18	0.19	0.21	0.24	0.24	0.26	0.28	0.29	0.31	0.32
2.4 m	W/m^2 K	0.28	0.34	0.45	0.57	0.63	0.74	0.85	0.91	1.02	1.08	1.19	1.36	1.36	1.48	1.59	1.65	1.76	1.82

Sources: Parts A through C reprinted with permission of the ASHRAE, from the 2001 *ASHRAE Handbook—Fundamentals*; Parts D and E from *ASHRAE Cooling and Heating Load Calculation Manual*, 1979. This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest. SI units appended by the authors.

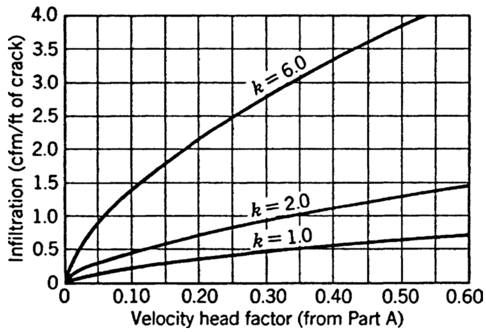
TABLE F.4 Approximate Infiltration through Doors and Windows of Small Buildings

Part A. Converting Wind Speed to Velocity Head Factor



Note: Design conditions are often assumed as:
Winter wind V_w = 15 mph (6.7 m/s) corresponding to a velocity head factor of 0.105
Summer wind V_w = 7.5 mph (3.4 m/s) corresponding to a velocity head factor of 0.028

Part B. Infiltration Rates for Velocity Head Factors



Note: Enter this graph with velocity head factor (from Part A) to find infiltration rate in cfm/ft of crack (using values of k found in Part C or D). L/s per m = (cfm/ft) (0.646).

TABLE F.4 Approximate Infiltration through Doors and Windows of Small Buildings (*Continued*)

Part C. Classifications of Windows for Infiltration		
Window Fit	**Wood Double-Hung (Locked)**	**Other Types**
Tight, $k = 1.0$	Weather stripped; average gap (1⁄64 in. [0.4 mm] crack).	Wood casement and awning windows; weather stripped.
		Metal casement windows; weather stripped.
Average, $k = 2.0$	Non–weather stripped; average gap (1⁄64 in. [0.4 mm] crack) or weather stripped; large gap (3⁄32 in. [2.4 mm] crack).	All types of vertical and horizontal sliding windows; weather stripped. If average gap (1⁄64 in. [0.4 mm] crack), this could be a tight-fitting window.
		Metal casement windows; non–weather stripped. If large gap (3⁄32 in. [2.4 mm] crack), this could be a loose-fitting window.
Loose, $k = 6.0$	Non–weather stripped; large gap (3⁄32 in. [2.4 mm] crack).	Vertical and horizontal sliding windows; non–weather stripped.

Part D. Classification of Residential-type Doors for Infiltration	
Door Fit	**Comments**
Tight, $k = 1.0$	Very small perimeter gap and perfect fit weather stripping—often characteristic of new doors.
Average, $k = 2.0$	Small perimeter gap having stop trim fitting properly around door; weather stripped.
Loose, $k = 6.0$	Large perimeter gap having poor fitting stop trim; weather stripped.
	or
	Small perimeter gap; no weather stripping.

Source: Reprinted with permission of ASHRAE, from *Cooling and Heating Load Calculation Manual*, 2nd edition, 1992. SI units appended by the authors.

APPENDIX G

Heating and Cooling Design Guidelines and Information

This appendix provides data to support the design and analysis processes presented in Chapters 9–11.

- G.1 Glazing Areas for Passive Solar Buildings
- G.2 Thermal Mass for Passive Solar Buildings
- G.3 Estimating Summer Heat Gains
- G.4 Passive Solar Building Characteristics
- G.5 Design Temperature Differences for Opaque Envelope Assemblies
- G.6 Heat Gains (Cooling Loads) through Glass
- G.7 Heat Gains (Cooling Loads) Due to Infiltration/Ventilation
- G.8 Heat Gains from Building Occupants
- G.9 Heat Gains from Office Equipment
- G.10 Heat Gains from Appliances
- G.11 Climate Data for Building Cooling
- G.12 Design Data for Earth Tubes
- G.13 Psychrometric Charts

G.1 GLAZING AREAS FOR PASSIVE SOLAR BUILDINGS

TABLE G.1 Design Guidelines for Passive Solar Glazing Area

	Area of Solar Glazing[a] as Ratio of Floor Area		*Approximate SSF Values*			
			Standard Performance[b]		*Superior Performance[c]*	
Location	**Low**	**High**	**Low**	**High**	**Low**	**High**
Birmingham, Alabama	0.09	0.18	22	37	34	58
Mobile, Alabama	0.06	0.12	26	44	34	60
Montgomery, Alabama	0.07	0.15	24	41	34	59
Phoenix, Arizona	0.06	0.12	37	60	48	75
Prescott, Arizona	0.10	0.20	29	48	44	72
Tucson, Arizona	0.06	0.12	35	57	45	73
Winslow, Arizona	0.12	0.24	30	47	48	74
Yuma, Arizona	0.04	0.09	43	66	51	78
Fort Smith, Arkansas	0.10	0.20	24	39	38	64
Little Rock, Arkansas	0.10	0.19	23	38	37	62
Bakersfield, California	0.08	0.15	31	50	42	67
Daggett, California	0.07	0.15	35	56	46	73
Fresno, California	0.09	0.17	29	46	41	65
Long Beach, California	0.05	0.10	35	58	44	72
Los Angeles, California	0.05	0.09	36	58	44	72
Mount Shasta, California	0.11	0.21	24	38	42	67
Needles, California	0.06	0.12	39	61	49	76
Oakland, California	0.07	0.15	35	55	46	72
Red Bluff, California	0.09	0.18	29	46	41	65
Sacramento, California	0.09	0.18	29	47	41	66
San Diego, California	0.04	0.09	37	61	46	74
San Francisco, California	0.06	0.13	34	54	45	71
Santa Maria, California	0.05	0.11	31	53	42	69
Colorado Springs, Colorado	0.12	0.24	27	42	47	74
Denver, Colorado	0.12	0.23	27	43	47	74
Eagle, Colorado	0.14	0.29	25	35	53	77
Grand Junction, Colorado	0.13	0.27	29	43	50	76
Pueblo, Colorado	0.11	0.23	29	45	48	75
Hartford, Connecticut	0.17	0.35	14	19	40	64
Wilmington, Delaware	0.15	0.29	19	30	39	63
Washington, DC	0.12	0.23	18	28	37	61
Apalachicola, Florida	0.05	0.10	28	47	36	61
Daytona Beach, Florida	0.04	0.08	30	51	36	63
Jacksonville, Florida	0.05	0.09	27	47	35	62
Miami, Florida	0.01	0.02	27	48	31	54
Orlando, Florida	0.03	0.06	30	52	37	63
Tallahassee, Florida	0.05	0.11	26	45	35	60
Tampa, Florida	0.03	0.06	30	52	36	63
West Palm Beach, Florida	0.01	0.03	30	51	34	59
Atlanta, Georgia	0.08	0.17	22	36	34	58
Augusta, Georgia	0.08	0.16	24	40	35	60
Macon, Georgia	0.07	0.15	25	41	35	59
Savannah, Georgia	0.06	0.13	25	43	35	60
Boise, Idaho	0.14	0.28	27	38	48	71
Lewiston, Idaho	0.15	0.29	22	29	44	65
Pocatello, Idaho	0.13	0.26	25	35	51	74
Chicago, Illinois	0.17	0.35	17	23	43	67
Moline, Illinois	0.20	0.39	17	22	46	70
Springfield, Illinois	0.15	0.30	19	28	42	67
Evansville, Indiana	0.14	0.27	19	29	37	61
Fort Wayne, Indiana	0.16	0.33	13	17	37	60
Indianapolis, Indiana	0.14	0.28	15	21	37	60
South Bend, Indiana	0.18	0.35	12	15	39	61
Burlington, Iowa	0.18	0.36	20	27	47	71
Des Moines, Iowa	0.21	0.43	19	25	50	75

TABLE G.1 Design Guidelines for Passive Solar Glazing Area (*Continued*)

	Area of Solar Glazing[a] as Ratio of Floor Area		*Approximate SSF Values*			
			Standard Performance[b]		*Superior Performance[c]*	
Location	**Low**	**High**	**Low**	**High**	**Low**	**High**
Mason City, Iowa	0.22	0.44	18	19	56	79
Sioux City, Iowa	0.23	0.46	20	24	53	76
Dodge City, Kansas	0.12	0.23	27	42	46	73
Goodland, Kansas	0.13	0.27	26	39	47	74
Topeka, Kansas	0.14	0.28	24	35	45	71
Wichita, Kansas	0.14	0.28	26	41	45	72
Lexington, Kentucky	0.13	0.27	17	26	35	58
Louisville, Kentucky	0.13	0.27	18	27	35	59
Baton Rouge, Louisiana	0.06	0.12	26	43	34	59
Lake Charles, Louisiana	0.06	0.11	24	41	32	57
New Orleans, Louisiana	0.05	0.11	27	46	35	61
Shreveport, Louisiana	0.08	0.15	26	43	36	61
Caribou, Maine	0.25	0.50	— NR[c]	—	53	74
Portland, Maine	0.17	0.34	14	17	45	69
Baltimore, Maryland	0.14	0.27	19	30	38	62
Boston, Massachusetts	0.15	0.29	17	25	40	64
Alpena, Michigan	0.21	0.42	— NR	—	47	69
Detroit, Michigan	0.17	0.34	13	17	39	61
Flint, Michigan	0.15	0.31	11	12	40	62
Grand Rapids, Michigan	0.19	0.38	12	13	39	61
Sault Ste. Marie, Michigan	0.25	0.50	— NR	—	50	70
Traverse City, Michigan	0.18	0.36	— NR	—	42	62
Duluth, Minnesota	0.25	0.50	— NR	—	50	70
International Falls, Minnesota	0.25	0.50	— NR	—	47	66
Minneapolis–St. Paul, Minnesota	0.25	0.50	— NR	—	55	76
Rochester, Minnesota	0.24	0.49	— NR	—	54	76
Jackson, Mississippi	0.08	0.15	24	40	34	59
Meridian, Mississippi	0.08	0.15	23	39	34	58
Columbia, Missouri	0.13	0.26	20	30	41	66
Kansas City, Missouri	0.14	0.29	22	32	44	70
Saint Louis, Missouri	0.15	0.29	21	33	41	65
Springfield, Missouri	0.13	0.26	22	34	40	65
Billings, Montana	0.16	0.32	24	31	53	76
Cut Bank, Montana	0.24	0.49	22	23	62	81
Dillon, Montana	0.16	0.32	24	32	54	77
Glasgow, Montana	0.25	0.50	— NR	—	55	75
Great Falls, Montana	0.18	0.37	23	28	56	77
Helena, Montana	0.20	0.39	21	25	55	77
Lewistown, Montana	0.19	0.38	21	25	54	76
Miles City, Montana	0.23	0.47	21	23	60	80
Missoula, Montana	0.18	0.36	15	16	47	68
Grand Island, Nebraska	0.18	0.36	24	33	51	76
North Omaha, Nebraska	0.20	0.40	21	29	51	76
North Platte, Nebraska	0.17	0.34	25	36	50	76
Scotts Bluff, Nebraska	0.16	0.31	24	36	49	74
Elko, Nevada	0.12	0.25	27	39	52	76
Ely, Nevada	0.12	0.23	27	41	50	77
Las Vegas, Nevada	0.09	0.18	35	56	48	75
Lovelock, Nevada	0.13	0.25	32	48	53	78
Reno, Nevada	0.11	0.22	31	48	49	76
Tonopah, Nevada	0.11	0.23	31	48	51	77
Winnemucca, Nevada	0.13	0.26	28	42	49	75
Concord, New Hampshire	0.17	0.34	13	15	45	68
Newark, New Jersey	0.13	0.25	19	29	39	64
Albuquerque, New Mexico	0.11	0.22	29	47	46	73
Clayton, New Mexico	0.10	0.20	28	45	45	73
Farmington, New Mexico	0.12	0.24	29	45	49	76
Los Alamos, New Mexico	0.11	0.22	25	40	44	72

TABLE G.1 Design Guidelines for Passive Solar Glazing Area (*Continued*)

	Area of Solar Glazing[a] as Ratio of Floor Area		*Approximate SSF Values*				
			Standard Performance[b]			*Superior Performance[c]*	
Location	**Low**	**High**	**Low**		**High**	**Low**	**High**
Roswell, New Mexico	0.10	0.19	30		49	45	73
Truth or Consequences, New Mexico	0.09	0.17	32		51	46	73
Tucumcari, New Mexico	0.10	0.20	30		48	45	73
Zuñi, New Mexico	0.11	0.21	27		43	45	73
Albany, New York	0.21	0.41	13		15	43	66
Binghamton, New York	0.15	0.30	—	NR	—	35	56
Buffalo, New York	0.19	0.37	—	NR	—	36	57
Massena, New York	0.25	0.50	—	NR	—	50	71
New York (Central Park), New York	0.15	0.30	16		25	36	59
Rochester, New York	0.18	0.37	—	NR	—	37	58
Syracuse, New York	0.19	0.38	—	NR	—	37	59
Asheville, North Carolina	0.10	0.20	21		35	36	61
Cape Hatteras, North Carolina	0.09	0.17	24		40	36	60
Charlotte, North Carolina	0.08	0.17	23		38	36	60
Greensboro, North Carolina	0.10	0.20	23		37	37	63
Raleigh–Durham, North Carolina	0.09	0.19	22		37	36	61
Bismarck, North Dakota	0.25	0.50	—	NR	—	56	77
Fargo, North Dakota	0.25	0.50	—	NR	—	51	72
Minot, North Dakota	0.25	0.50	—	NR	—	52	72
Akron–Canton, Ohio	0.15	0.31	12		16	35	57
Cincinnati, Ohio	0.12	0.24	15		23	35	57
Cleveland, Ohio	0.15	0.31	11		14	34	55
Columbus, Ohio	0.14	0.28	13		18	35	57
Dayton, Ohio	0.14	0.28	14		20	36	59
Toledo, Ohio	0.17	0.34	13		17	38	61
Youngstown, Ohio	0.16	0.32	—	NR	—	34	54
Oklahoma City, Oklahoma	0.11	0.22	25		41	41	67
Tulsa, Oklahoma	0.11	0.22	24		38	40	65
Astoria, Oregon	0.09	0.19	21		34	37	60
Burns, Oregon	0.13	0.25	23		32	47	71
Medford, Oregon	0.12	0.24	21		32	38	60
North Bend, Oregon	0.09	0.17	25		42	38	64
Pendleton, Oregon	0.14	0.27	22		30	43	64
Portland, Oregon	0.13	0.26	21		31	38	60
Redmond, Oregon	0.13	0.27	26		38	47	71
Salem, Oregon	0.12	0.24	21		32	37	59
Allentown, Pennsylvania	0.15	0.29	16		24	39	63
Erie, Pennsylvania	0.17	0.34	—	NR	—	35	55
Harrisburg, Pennsylvania	0.13	0.26	17		26	38	62
Philadelphia, Pennsylvania	0.15	0.29	19		29	38	62
Pittsburgh, Pennsylvania	0.14	0.28	12		16	33	55
Wilkes Barre–Scranton, Pennsylvania	0.16	0.32	13		18	37	60
Providence, Rhode Island	0.15	0.30	17		24	40	64
Charleston, South Carolina	0.07	0.14	25		41	34	59
Columbia, South Carolina	0.08	0.17	25		41	36	61
Greenville–Spartanburg, South Carolina	0.08	0.17	23		38	36	60
Huron, South Dakota	0.25	0.50	—	NR	—	58	79
Pierre, South Dakota	0.22	0.43	21		23	58	80
Rapid City, South Dakota	0.15	0.30	23		32	51	76
Sioux Falls, South Dakota	0.22	0.45	18		19	57	79
Chattanooga, Tennessee	0.09	0.19	19		32	33	56
Knoxville, Tennessee	0.09	0.18	20		33	33	56
Memphis, Tennessee	0.09	0.19	22		36	36	60
Nashville, Tennessee	0.10	0.21	19		30	33	55
Abilene, Texas	0.09	0.18	29		47	41	68
Amarillo, Texas	0.11	0.22	29		46	45	72
Austin, Texas	0.06	0.13	27		46	37	63
Brownsville, Texas	0.03	0.06	27		46	32	57

TABLE G.1 Design Guidelines for Passive Solar Glazing Area (*Continued*)

	Area of Solar Glazing[a] as Ratio of Floor Area		*Approximate SSF Values*			
			Standard Performance[b]		*Superior Performance[c]*	
Location	**Low**	**High**	**Low**	**High**	**Low**	**High**
Corpus Christi, Texas	0.05	0.09	29	49	36	63
Dallas, Texas	0.08	0.17	27	44	38	64
Del Rio, Texas	0.06	0.12	30	50	39	66
El Paso, Texas	0.09	0.17	32	53	45	72
Fort Worth, Texas	0.09	0.17	26	44	38	64
Houston, Texas	0.06	0.11	25	43	34	59
Laredo, Texas	0.05	0.09	31	52	39	64
Lubbock, Texas	0.09	0.19	30	49	44	72
Lufkin, Texas	0.07	0.14	26	43	35	61
Midland–Odessa, Texas	0.09	0.18	32	52	44	72
Port Arthur, Texas	0.06	0.11	26	44	34	60
San Angelo, Texas	0.08	0.15	29	48	40	67
San Antonio, Texas	0.06	0.12	28	48	38	64
Sherman, Texas	0.10	0.20	25	41	38	64
Waco, Texas	0.08	0.15	27	45	38	64
Wichita Falls, Texas	0.10	0.20	27	45	41	67
Bryce Canyon, Utah	0.13	0.25	26	39	52	78
Cedar City, Utah	0.12	0.24	28	43	48	75
Salt Lake City, Utah	0.13	0.26	27	39	48	72
Burlington, Vermont	0.22	0.43	— NR	—	46	68
Norfolk, Virginia	0.09	0.19	23	38	37	62
Richmond, Virginia	0.11	0.22	21	34	37	61
Roanoke, Virginia	0.11	0.23	21	34	37	61
Olympia, Washington	0.12	0.23	20	29	38	59
Seattle-Tacoma, Washington	0.11	0.22	21	30	39	59
Spokane, Washington	0.20	0.39	20	24	48	68
Yakima, Washington	0.18	0.36	24	31	49	70
Charleston, West Virginia	0.13	0.25	16	24	32	54
Huntington, West Virginia	0.13	0.25	17	27	34	57
Eau Claire, Wisconsin	0.25	0.50	— NR	—	53	75
Green Bay, Wisconsin	0.23	0.46	— NR	—	53	75
La Crosse, Wisconsin	0.21	0.43	— NR	—	52	75
Madison, Wisconsin	0.20	0.40	15	17	51	74
Milwaukee, Wisconsin	0.18	0.35	15	18	48	71
Casper, Wyoming	0.13	0.26	27	39	53	78
Cheyenne, Wyoming	0.11	0.21	25	39	47	74
Rock Springs, Wyoming	0.14	0.28	26	38	54	79
Sheridan, Wyoming	0.16	0.31	22	30	52	75
CANADA						
Edmonton, Alberta	0.25	0.50	— NR	—	54	72
Suffield, Alberta	0.25	0.50	28	30	67	85
Nanaimo, British Columbia	0.13	0.26	26	35	45	66
Vancouver, British Columbia	0.13	0.26	20	28	40	60
Winnipeg, Manitoba	0.25	0.50	— NR	—	54	74
Dartmouth, Nova Scotia	0.14	0.28	17	24	45	70
Moosonee, Ontario	0.25	0.50	— NR	—	48	67
Ottawa, Ontario	0.25	0.50	— NR	—	59	80
Toronto, Ontario	0.18	0.36	17	23	44	68
Normandin, Quebec	0.25	0.50	— NR	—	54	74

Source: Adapted from J. D. Balcomb et al. (1980). *Passive Solar Design Handbook*, Vol. 2 (*Passive Solar Design Analysis*), U.S. Department of Energy, Washington, DC.

NR = not recommended. SSF = solar savings fraction.

[a]Due south–facing openings are assumed.

[b]Double-glazed, clear glass (approximately equal to window 3, Table E.15).

[c]Either movable window insulation of R-9 (SI:R-1.6), in place from 5:30 P.M. to 7:30 A.M., solar time, or superwindows (approximately equal to window 7 or 12, Table E.15) with an overall U-factor near 0.30 (U-SI of 1.7).

G.2 THERMAL MASS FOR PASSIVE SOLAR BUILDINGS

TABLE G.2 Design Guidelines for Passive Solar Thermal Mass

Expected Solar Savings Fraction (SSF), %	*Thermal Storage by Weight/Collector Area*				*Recommended Effective[a] Thermal Storage Area Per Unit Area of Solar Collection Area*	
	Water		*Masonry*		*Water Surface Area[b]*	*Masonry Surface Area[c]*
	lb/ft^2	kg/m^2	lb/ft^2	kg/m^2	Collector Surface Area	Collector Surface Area
10	6	29	30	147	0.1	0.7
20	12	59	60	293	0.2	1.5
30	18	88	90	440	0.3	2.2
40	24	117	120	586	0.4	2.9
50	30	147	150	733	0.5	3.7
60	36	176	180	879	0.6	4.4
70	42	205	210	1026	0.7	5.1
80	48	234	240	1172	0.8	5.9
90	54	264	270	1319	0.9	6.6

Source: Adapted from J. D. Balcomb et al. (1980). *Passive Solar Design Handbook*, Vol. 2 (*Passive Solar Design Analysis*), U.S. Department of Energy, Washington, DC.

[a]Effective area is that area exposed at some point to direct sun during a clear winter day.

[b]For a water container 12 in. (300 mm) thick.

[c]For a 4-in.- (100-mm)-thick brick, density 123 lb/ft^3 (1970 kg/m^3).

G.3 ESTIMATING SUMMER HEAT GAINS

TABLE G.3 Approximate Summer Heat Gains from Occupants, Equipment, Lighting, and Envelope

Part A. Internal Heat Sources—People and Equipment								
	Area per Person[a]		*I-P Sensible Heat Gain (Btu/h ft^2 of Floor Area)*			*SI Sensible Heat Gain (W/m^2 of Floor Area)*		
Function	ft^2	m^2	People[b]	Equipment[c]	Total	People[b]	Equipment[c]	Total
Office, U.S.[c, d]	180–100	16.7–9.3	1.3–2.3	0.4–1.1	1.7–3.4	4.1–7.3	1.2–3.4	5.3–10.7
Office, Europe[e]			1–1.6	2.2–4.2	3.2–5.8	3–5	7–13.1	10–18.1
School: elementary, U.S.	100–20	9.3–1.9	2.3–11.5	0–0.6	2.3–12.1	7.3–36.3	0–2.0	7.3–38.3
Schools, Europe[e]			3.8–8.0	0–0.6	3.8–8.6	12–25.2	0–2.0	12.0–27.2
School: secondary, college	150–100	13.9–9.3	1.7–2.6	0–0.6	1.7–3.2	5.4–8.2	0–2.0	5.4–10.2
Health care								
Sleeping (hospital)	240	22.3	0.9	0.6[e]	1.5	2.8	2.0[e]	4.8
In-patient (clinic)	120	11.1	1.9	Varies	1.9+	6.0	Varies	6.0+
Assembly: fixed seats	15	1.4	14.0	—	14.0	44.2	—	44.2
standing space, concentrated use	15–7	1.4–0.7	21.0–45.0	0–0.5	21.0–45.5	66.3–142.0	0–1.6	66.3–143.6
Restaurant:[f]								
Fast food: dining area	15	1.4	17	3.4	20.4	53.6	10.7	64.3
Kitchen, refrigeration				17.1	17.1		54.0	54.0
Sit-down: dining area	25	2.3	10.2	5.1	15.3	32.2	16.1	48.3
Kitchen, refrigeration				7.2	7.2		22.7	22.7
Mercantile: street floor	50–30	4.7–2.8	6.3–10.5	3.4	9.7–13.9	19.9–33.1	10.7	30.6–43.8
Other sales floors	60–50	5.6–4.7	5.3–6.3	3.4	8.7–9.7	16.7–19.9	10.7	27.4–30.6
Shopping center, Europe[e]			3.2	0.3–1.3	3.5–4.5	10	1.0–4.0	11.0–14.0
Warehouse	1000–300	92.9–27.9	0.4–1.2	—	0.4–1.2	1.3–3.8	—	1.3–3.8
Hotels, nursing homes	300–200	27.9–18.6	0.8–1.2	3.4	4.2–4.6	2.5–3.8	10.7	13.2–14.5
Apartments[g]	300–200	27.9–18.6	0.8–1.2	See note *g*	See note *g*	2.5–3.8	See note *g*	See note *g*

TABLE G.3 Approximate Summer Heat Gains from Occupants, Equipment, Lighting, and Envelope (*Continued*)

Part B. Internal Heat Sources—Electric Lighting						
	I-P Sensible Heat Gain[h] (Btu/h ft^2 of Floor Area)			***SI Sensible Heat Gain[h] (W/m^2 of Floor Area)***		
Function	**DF (daylight factor)<1**	**1<DF<4[h]**	**DF>4[h]**	**DF<1**	**1<DF<4[h]**	**DF>4[h]**
Office	5.1	2.0	0.5	16.1	6.3	1.6
School: elementary	6.3–6.8	2.5–2.7	0.6–0.7	19.9–21.5	7.9–8.5	1.9–2.2
School: secondary, college	6.3–6.8	2.5–2.7	0.6–0.7	19.9–21.5	7.9–8.5	1.9–2.2
Health care						
Sleeping (hospital)	6.8	2.7	0.7	21.5	8.5	2.2
In-patient (clinic)	6.8	2.7	0.7	21.5	8.5	2.2
Assembly	3.8	1.5	0.4	12.0	4.7	1.3
Restaurants[i]	6.3	2.5	0.6	19.9	7.9	1.9
Mercantile	5.1–6.8	2.0–2.7	0.5–0.7	16.1–21.5	6.3–8.5	1.6–2.2
Warehouse	2.4	1.0	0.2	7.6	3.2	0.6
Hotels, nursing homes	6.8	2.7	0.7	21.5	8.5	2.2
Apartments[g]	Up to 6.8	Up to 2.7	Up to 0.7	Up to 21.5	Up to 8.5	Up to 2.2

Part C. Heat Gain through Envelope[j]				
	(Btu/h ft^2 of Floor Area) Outdoor Design Temperature		***(W/m^2 of Floor Area) Outdoor Design Temperature***	
	90°F	**100°F**	**32°C**	**38°C**
I. Gains through externally shaded windows[k]:				
Find ratio, $\frac{\text{total window area}}{\text{total floor area}}$, then multiply by	16	21	50	66
II. Gains through opaque walls:				
Find ratio, $\frac{\text{total opaque wall area}}{\text{total floor area}} \times (U_{\text{wall}})$, then multiply by	15	25	8	14
III. Gains through roofs:				
Find ratio, $\frac{\text{total opaque roof area}}{\text{total floor area}} \times (U_{\text{roof}})$, then multiply by	35	45	19	25

Part D. Summary Gains

I. Passive cooling systems for (thermally) "open" buildings
- Cross-ventilation
- Stack ventilation
- Nighttime or "open" hours of thermal mass/night ventilation

Total gains: Add Parts A, B, and C to obtain cooling load, in Btu/h ft^2 (W/m^2), of floor area.

II. Passive cooling systems for (thermally) "closed" buildings
- Roof ponds
- Evaporative cooling
- Daytime or "closed" hours of thermal mass/night ventilation

Total gains: Add Parts A, B, C, and E to obtain cooling load, in Btu/h ft^2 (W/m^2), of floor area.

Part E. Gains from Infiltration/Ventilation of "Closed" Buildings				
	Outdoor Design Temperature		***Outdoor Design Temperature***	
	90°F	**100°F**	**32°C**	**38°C**
Infiltration:				
Find ratio, $\frac{\text{total window + opaque wall area}}{\text{total floor area}}$, then multiply by	1.0	1.9	3.2	6.0
Ventilation:				
Find known, $\frac{\text{total cfm of outdoor air}}{\text{total floor area, ft}^2}$, then multiply by	16	27	—	—
Find known, $\frac{\text{total L/s of outdoor air}}{\text{total floor area, m}^2}$, then multiply by	—	—	9.9	16.8

[a]Lower density from elevator population estimates, Chapter 32; higher density from fire population estimates, Chapter 19. Lower density for whole-building estimates; higher density for single-space estimates.

[b]Sensible gains per adult from Table G.8 for activities as stated.

[c]The typical "miscellaneous" load of 1 W/ft^2 (10.8 W/m^2) produces 3.4 Btu/h ft^2.

TABLE G.3 Approximate Summer Heat Gains from Occupants, Equipment, Lighting, and Envelope (*Continued*)

[d]P. Komor, "Space Cooling Demand from Office Plug Loads," in *ASHRAE Journal*, December 1997. This is considerably lower than the typical 2 to 4 W/ft^2 (21.5 to 43.1 W/m^2) for offices used by many designers.

[e]Adapted from S. R. Hastings (1994). *Passive Solar Commercial and Institutional Buildings*, International Energy Agency, John Wiley & Sons, Chichester, UK.

[f]Based on total area of restaurant + kitchen. From ACSA (1994). *Design with PV*. Association of Collegiate Schools of Architecture, Washington, DC.; data from Electric Power Research Institute.

[g]Residential internal gains are often assumed at 230 Btu/h per occupant plus 1200 to 1600 Btu/h total from appliances (68 W per person, plus 350 to 470 W total from appliances).

[h]Adapted from Northwest Power Planning Council (1983). *Maximum Lighting Standards*, Portland, OR. Values shown for DF ≥ 1 assume automatic dimming in the presence of daylight.

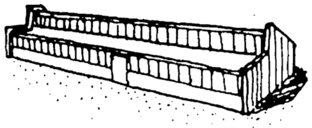
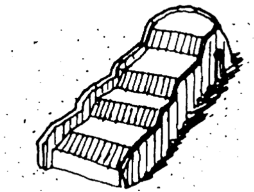
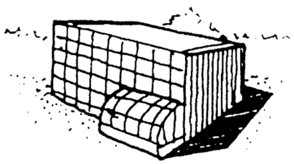
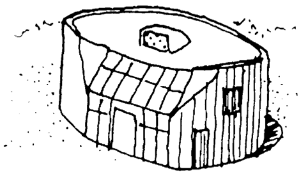
[i]Lighting load is often much lower in sit-down than in fast-food restaurants.

[j]Averaged from the more specific data found in Table G.5.

[k]If windows are not externally shaded, see Table G.6 for multipliers, which will vary by orientation.

G.4 PASSIVE SOLAR BUILDING CHARACTERISTICS

TABLE G.4 Design Data for Some Early Passive Solar Buildings

	Name, Function Location	Floor Area (ft^2)	Area Ratio, South Glass / Floor Area	System Type (see Apx. I)	Approx. LCR		Approx. SSF	
					ACH = 1.0	ACH = 0.5	ACH = 1.0	ACH = 0.5
	Dove Publications, Pecos, N.M.							
	Office	2660	0.37	DGB1 and WWB4	37[a]	25[a]	43%[a]	51%[a]
	Warehouse	5040	0.11	DGC1				
	Karen Terry House, Santa Fe, N.M.	850	0.45	DGC1	22	17	52%	60%
	Kelbaugh House, Princeton, N.J.	1640[b]	0.49[c]	TWE2, DGB1, and SSB4	13	9	62%	72%
	First Village, Unit 1, Santa Fe, N.M.	1800[b]	0.22[c]	SSE1	49	31	38%	52%

LCR = load-to-collector ratio; ACH = air change per hour; SSF = solar savings fraction.

[a]Treating office and warehouse as one large zone.

[b]Not including sunspace floor area.

[c]Includes sunspace south glazing, but not sunspace floor area.

G.5 DESIGN TEMPERATURE DIFFERENCES FOR OPAQUE ENVELOPE ASSEMBLIES

TABLE G.5 Design Equivalent Temperature Differences (DETD)

Part A. Mass Walls, Roofs, and Floors																								
SI Units												***Outdoor Design Temperature***	*I-P Units*											
29.4°C		**32.2**			**35.0**			**37.7**		**40.5**	**43.3**	***Daily Temperature***	**85°F**		**90**			**95**			**100**		**105**	**110**
L	**M**	**L**	**M**	**H**	**L**	**M**	**H**	**M**	**H**	**H**	**H**	***Range*[a]**	**L**	**M**	**L**	**M**	**H**	**L**	**M**	**H**	**M**	**H**	**H**	**H**
												Walls												
5.7	3.5	8.5	6.3	3.5	11.3	9.1	6.3	11.8	9.1	11.8	14.6	1. Masonry walls, 200-mm (8-in.) block or brick	10.3	6.3	15.3	11.3	6.3	20.3	16.3	11.3	21.3	16.3	21.3	26.3
5.0	2.7	7.7	5.5	2.7	10.5	8.3	5.5	11.1	8.3	11.1	13.8	2. Partitions, frame	9.0	5.0	14.0	10.0	5.0	19.0	15.0	10.0	20.0	15.0	20.0	25.0
1.4	0.0	4.2	1.9	0.0	6.9	4.7	1.9	7.5	4.7	7.5	10.3	masonry	2.5	0	7.5	3.5	0	12.5	8.5	3.5	13.5	8.5	13.5	18.5
												Ceilings and Roofs												
												1. Ceilings under naturally vented attic or vented flat roof												
21.1	18.8	23.8	21.6	18.8	26.6	24.4	21.6	27.2	24.4	27.2	30.0	—dark	38.0	34.0	43.0	39.0	34.0	48.0	44.0	39.0	49.0	44.0	49.0	54.0
16.6	14.9	19.4	17.2	14.4	22.2	20.0	17.2	22.7	20.0	22.7	25.5	—light	30.0	26.0	35.0	31.0	26.0	40.0	36.0	31.0	41.0	36.0	41.0	46.0
												2. Built-up roof, no ceiling												
21.1	18.8	23.3	21.6	18.8	26.6	24.4	21.6	27.2	24.4	27.2	30.0	—dark	38.0	34.0	43.0	39.0	34.0	48.0	44.0	39.0	49.0	44.0	49.0	54.0
16.6	14.9	19.4	17.2	14.4	22.2	20.2	17.2	22.7	20.0	22.7	25.5	—light	30.0	26.0	35.0	31.0	26.0	40.0	36.0	31.0	41.0	36.0	41.0	46.0
5.0	2.7	7.7	5.5	2.7	10.5	8.3	5.5	11.1	8.3	11.1	13.8	3. Ceilings under unconditioned rooms	9.0	5.0	14.0	10.0	5.0	19.0	15.0	10.0	20.0	15.0	20.0	25.0
												Floors												
5.0	2.7	7.7	5.5	2.7	10.5	8.3	5.5	11.1	8.3	11.1	13.8	1. Over unconditioned rooms	9.0	5.0	14.0	10.0	5.0	19.0	15.0	10.0	20.0	15.0	20.0	25.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2. Over basement, enclosed crawl space, or concrete slab on ground	0	0	0	0	0	0	0	0	0	0	0	0
5.0	2.7	7.7	5.5	2.7	10.5	8.3	5.5	11.1	8.3	11.1	13.8	3. Over open crawl space	9.0	5.0	14.0	10.0	5.0	19.0	15.0	10.0	20.0	15.0	20.0	25.0

TABLE G.5 Design Equivalent Temperature Differences (DETD) (*Continued*)

Part B. Frame Walls and Doors																								
SI Units												***Outdoor Design Temperature Daily Temperature Range***[a]	***I-P Units***											
29.4°C		**32**			**35**			**38**		**41**	**43**		**85°F**		**90**			**95**			**100**		**105**	**110**
L	**M**	**L**	**M**	**H**	**L**	**M**	**H**	**M**	**H**	**H**	**H**	**Orientation**	**L**	**M**	**L**	**M**	**H**	**L**	**M**	**H**	**M**	**H**	**H**	**H**
4	2	7	4	2	10	7	4	10	7	10	13	North	8	3	13	8	3	18	13	8	18	13	18	23
8	5	11	8	5	13	11	8	13	11	13	16	NE and NW	14	9	19	14	9	24	19	14	24	19	24	29
10	7	13	10	7	16	13	10	16	13	16	18	East and West SE	18	13	23	18	13	28	23	18	28	23	28	33
9	6	12	9	6	14	12	9	14	12	14	17	and SW	16	11	21	16	11	26	21	16	26	21	26	31
6	3	9	6	3	12	9	6	12	9	12	14	South	11	6	16	11	6	21	16	11	21	16	21	26

Source: Part A, Previously adapted, with the permission of ASHRAE, from the *1981 ASHRAE Handbook—Fundamentals*; Part B, Previously adapted, with the permission of ASHRAE, from the *1997 ASHRAE Handbook—Fundamentals*. This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

[a]Daily temperature range: L (low), M (medium), H (high).

From Appendix B, mean daily range column: L is less than 16F° (9C°); M is 16 to 25F° (9 to 14C°); H is greater than 25F° (14C°).

G.6 HEAT GAINS (COOLING LOADS) THROUGH GLASS

TABLE G.6 Design Cooling Load Factors through Glass

Part A. SI: W/m^2																			
Outdoor Design	***Regular Single Glass***						***Regular Double Glass***						***Heat-Absorbing Double Glass***						***Clear Triple Glass***		
Temp. (°C)[a]	**29.4**	**32.2**	**35.0**	**37.7**	**40.5**	**43.3**	**29.4**	**32.2**	**35.0**	**37.7**	**40.5**	**43.3**	**29.4**	**32.2**	**35.0**	**37.7**	**40.5**	**43.3**	**29.4**	**32.2**	**35.0**
No Awnings or Inside Shading																					
North	72.6	85.2	97.8	110.4	123.0	138.8	59.9	66.2	75.8	82.0	88.3	94.7	37.9	44.1	53.7	60.0	66.2	72.6	53.7	60.0	63.1
NE and NW	176.6	189.3	202.0	214.6	227.1	243.0	145.1	151.4	161.0	167.2	173.6	179.9	85.1	91.4	101.0	107.2	113.6	119.9	132.6	135.7	138.9
East and west	255.5	268.1	280.8	293.4	306.0	321.9	214.6	220.9	230.3	236.7	243.0	249.2	132.6	138.9	148.2	154.6	160.9	167.2	195.7	198.8	202.6
SE and SW	220.9	233.4	246.0	258.8	271.3	287.1	186.1	192.4	202.0	208.2	214.6	220.9	110.4	116.8	126.2	132.6	138.9	145.1	167.2	173.6	176.7
South	126.2	138.9	151.4	164.0	176.7	192.4	104.1	110.4	119.9	126.2	132.6	138.9	66.0	75.8	75.8	82.0	88.3	94.7	94.7	97.9	104.1
Horiz. skylight	504.8	517.4	530.0	542.7	555.2	571.0	438.6	444.9	454.3	460.7	467.0	473.2	280.8	296.6	296.6	302.9	309.1	315.6	397.6	400.7	407.0
Draperies or Venetian Blinds																					
North	47.3	60.0	72.6	85.1	97.9	113.6	37.9	44.1	53.7	60.0	66.2	72.6	28.3	34.7	44.1	50.4	56.8	63.1	34.7	37.9	44.2
NE and NW	101.0	113.6	126.2	138.9	151.4	167.2	85.1	91.4	101.0	107.2	113.6	119.9	63.1	69.4	78.9	85.1	91.4	97.9	75.8	82.0	85.1
East and west	151.4	164.0	176.7	189.3	202.0	217.7	132.6	138.9	148.2	154.6	161.0	167.2	94.7	101.0	110.4	116.8	123.0	129.3	119.9	123.0	129.3
E and SW	126.2	138.9	151.4	164.0	176.7	192.4	110.4	116.8	126.2	132.6	138.9	145.1	75.8	82.0	91.4	97.9	104.1	110.4	101.0	104.1	107.2
South	72.5	85.1	97.9	110.4	123.0	138.9	63.1	69.4	78.9	85.1	91.4	97.9	47.3	53.7	63.1	75.8	75.8	82.0	56.8	60.0	66.2
Roller Shades Half-Drawn																					
North	56.8	69.4	82.0	92.7	102.2	123.0	47.3	53.7	63.1	69.4	75.8	82.0	31.6	37.9	47.3	53.7	60.0	66.2	41.0	44.2	47.3
NE and NW	126.2	138.9	151.4	164.0	176.7	192.4	119.9	126.2	135.7	142.0	148.2	154.6	75.8	82.0	91.4	97.9	104.1	110.4	107.2	110.4	110.4
East and west	192.5	205.0	217.7	230.3	243.0	258.8	170.3	176.7	186.1	192.4	198.8	205.0	110.4	116.8	126.2	132.5	138.9	145.1	154.6	154.6	157.8
SE and SW	164.0	176.7	189.3	202.0	214.6	230.3	145.1	151.4	161.0	167.2	173.6	179.9	94.7	101.0	110.4	123.0	123.0	129.3	129.3	132.6	135.7
South	91.4	104.1	116.8	129.3	142.0	157.8	85.1	91.4	101.0	107.2	113.6	119.9	56.8	63.1	72.6	78.9	85.1	91.4	78.9	82.0	82.0
Awnings[b]																					
North	63.1	75.8	88.3	101.0	113.6	129.3	41.0	47.3	56.8	63.1	69.4	75.8	31.6	37.9	47.3	53.7	60.0	66.2	34.7	37.9	41.0
NE and NW	66.2	78.9	91.4	104.1	116.8	132.6	44.2	50.4	60.0	66.2	72.6	78.9	34.7	41.0	50.4	56.8	63.1	69.4	37.9	41.0	44.2
East and west	69.4	82.0	94.7	107.2	119.9	135.7	44.2	50.4	60.0	66.2	72.6	78.9	37.9	44.2	53.6	60.0	66.2	72.6	37.9	41.0	44.2
SE and SW	66.2	78.9	91.4	104.1	116.8	132.6	44.2	50.4	60.0	66.2	72.6	78.9	34.7	41.0	50.4	56.8	63.1	69.4	37.9	41.0	44.2
South	66.2	75.8	88.3	101.0	113.6	129.3	41.0	47.3	56.8	63.1	69.4	75.8	34.7	41.0	50.4	56.8	63.1	69.4	34.7	37.9	41.0

G.6 HEAT GAINS (COOLING LOADS) THROUGH GLASS (*Continued*)

Part B. I-P: Btu/h ft^2

Outdoor Design Temp. (°F)[a]	*Regular Single Glass*						*Regular Double Glass*						*Heat-Absorbing Double Glass*						*Clear Triple Glass*		
	85	**90**	**95**	**100**	**105**	**110**	**85**	**90**	**95**	**100**	**105**	**110**	**85**	**90**	**95**	**100**	**105**	**110**	**85**	**90**	**95**
No Awnings or Inside Shading																					
North	23	27	31	35	39	44	19	21	24	26	28	30	12	14	17	19	21	23	17	19	20
NE and NW	56	60	64	68	72	77	46	48	51	53	55	57	27	29	32	34	36	38	42	43	44
East and west	81	85	89	93	97	102	68	70	73	75	77	79	42	44	47	49	51	53	62	63	64
SE and SW	70	74	78	82	86	91	59	61	64	66	68	70	35	37	40	42	44	46	53	55	56
South	40	44	48	52	56	61	33	35	38	40	42	44	19	21	24	26	28	30	30	31	33
Horiz. skylight	160	164	168	172	176	181	139	141	144	146	148	150	89	91	94	96	98	100	126	127	129
Draperies or Venetian Blinds																					
North	15	19	23	27	31	36	12	14	17	19	21	23	9	11	14	16	18	20	11	12	14
NE and NW	32	36	40	44	48	53	27	29	32	34	36	38	20	22	25	27	29	31	24	26	27
East and west	48	52	56	60	64	69	42	44	47	49	51	53	30	32	35	37	39	41	38	39	41
SE and SW	40	44	48	52	56	61	35	37	40	42	44	46	24	26	29	31	33	35	32	33	34
South	23	27	31	35	39	44	20	22	25	27	29	31	15	17	20	22	24	26	18	19	21
Roller Shades Half-Drawn																					
North	18	22	26	30	34	39	15	17	20	22	24	26	10	12	15	17	19	21	13	14	15
NE and NW	40	44	48	52	56	61	38	40	43	45	47	49	24	26	29	31	33	35	34	35	35
East and west	61	65	69	73	77	82	54	56	59	61	63	65	35	37	40	42	44	46	49	49	50
SE and SW	52	56	60	64	68	73	46	48	51	53	55	57	30	32	35	37	39	41	41	42	43
South	29	33	37	41	45	50	27	29	32	34	36	38	18	20	23	25	27	29	25	26	26
Awnings[b]																					
North	20	24	28	32	36	41	13	15	18	20	22	24	10	12	15	17	19	21	11	12	13
NE and NW	21	25	29	33	37	42	14	16	19	21	23	25	11	13	16	18	20	22	12	13	14
East and west	22	26	30	34	38	43	14	16	19	21	23	25	12	14	17	19	21	23	12	13	14
SE and SW	21	25	29	33	37	42	14	16	19	21	23	25	11	13	16	18	20	22	12	13	14
South	21	24	28	32	36	41	13	15	18	20	22	24	11	13	16	18	20	22	11	12	13

Source: Previously adapted, with the permission of ASHRAE, from the *1981 ASHRAE Handbook—Fundamentals.* This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

[a]Based on indoor design temperature of 75°F (23.8°C) and outdoor design temperatures as indicated. Interpolate to obtain factors for outdoor design temperatures other than those given.

[b]For other external shading devices that completely shade the glass at any orientation, use the values for "Awnings, north."

G.7 HEAT GAINS (COOLING LOADS) DUE TO INFILTRATION/VENTILATION

TABLE G.7 Sensible Cooling Load Factors Due to Infiltration and Ventilation

Design Temperature °C:									Design Temperature °F:					
29.4	32.2	35.0	37.7	41.5	43.3	Units	Condition	Units	85	90	95	100	105	110
2.2	3.5	4.7	6.0	6.9	8.2	W/m^2	Infiltration, per gross exposed wall area	Btu/h ft^2	0.7	1.1	1.5	1.9	2.2	2.6
6.8	9.9	13.6	16.7	19.8	23.6	W per L/s	Mechanical ventilation	Btu/h per cfm	11.0	16.0	22.0	27.0	32.0	38.0

Source: Previously adapted, with the permission of ASHRAE, from the *1981 ASHRAE Handbook—Fundamentals.* This citation to an older version of the *Handbook* is intentional and provides access to historic reference information of ongoing interest.

G.8 HEAT GAINS FROM BUILDING OCCUPANTS

TABLE G.8 Rates of Heat Gain from Occupants of Conditioned Spaces

		Heat Gain							
		W				*Btu/h*			
Activity	Location	Adult Male	Adjusted[b]	Sensible[a] Heat	Latent[a] Heat	Adult Male	Adjusted[b]	Sensible[a] Heat	Latent[a] Heat
Seated at theater	Theater, matinee	115	95	65	30	390	330	225	105
Seated at theater, night	Theater, night	115	105	70	35	390	350	245	105
Seated, very light work	Offices, hotels, apartments	130	115	70	45	450	400	245	155
Moderately active office work	Offices, hotels, apartments	140	130	75	55	475	450	250	200
Standing, light work; walking	Department or retail store	160	130	75	55	550	450	250	200
Walking, standing	Drug store, bank	160	145	75	70	550	500	250	250
Sedentary work	Restaurant[c]	170	160	80	80	590	550	275	275
Light bench work	Factory	235	220	80	140	800	750	275	475
Moderate dancing	Dance hall	265	250	90	160	900	850	305	545
Walking 4.8 km/h (3 mph), light machine work	Factory	295	295	110	185	1000	1000	375	625
Bowling[d]	Bowling alley	440	425	170	255	1500	1450	580	870
Heavy work	Factory	440	425	170	255	1500	1450	580	870
Heavy machine work, lifting	Factory	470	470	185	285	1600	1600	635	965
Athletics	Gymnasium	585	525	210	315	2000	1800	710	1090

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]All values are rounded to the nearest 5 W (and 5 Btu/h). Based on 75°F (24°C) room dry-bulb temperature. For 80°F (27°C) room dry-bulb temperature, the total heat remains the same but the sensible heat values should be decreased by approximately 20% and the latent heat values increased accordingly.

[b]Adjusted heat gain based on the normal percentage of men, women, and children for the application listed, assuming that the gain from an adult female is 85% (and from children 75%) of that from an adult male.

[c]Adjusted heat gain includes 60 Btu/h (18 W) for food per individual: 50% sensible, 50% latent.

[d]Assume only one person per alley actually bowling and all others as sitting, standing, or walking slowly.

G.9 HEAT GAINS FROM OFFICE EQUIPMENT

TABLE G.9 Rates of Heat Gain from Office Equipment

Equipment Description	Nameplate Power, W	Average Power, W
Desktop computer[a]		
Manufacturer A (model A); 2.8 GHz processor, 1 GB RAM	480	73
Manufacturer A (model B); 2.6 GHz processor, 2 GB RAM	480	49
Manufacturer B (model A); 3.0 GHz processor, 2 GB RAM	690	77
Manufacturer B (model B); 3.0 GHz processor, 2 GB RAM	690	48
Manufacturer A (model C); 2.3 GHz processor, 3 GB RAM	1200	97
Laptop computer[b]		
Manufacturer 1; 2.0 GHz processor, 2 GB RAM, 17 in. screen	130	36
Manufacturer 1; 1.8 GHz processor, 1 GB RAM, 17 in. screen	90	23
Manufacturer 1; 2.0 GHz processor, 2 GB RAM, 14 in. screen	90	31
Manufacturer 2; 2.13 GHz processor, 1 GB RAM, 14 in. screen, tablet PC	90	29
Manufacturer 2; 366 MHz processor, 130 MB RAM (4 in. screen)	70	22
Manufacturer 3; 900 MHz processor, 256 MB RAM (10.5 in. screen)	50	12
Flat-panel monitor[c]		
Manufacturer X (model A); 30 in. screen	383	90
Manufacturer X (model B); 22 in. screen	360	36
Manufacturer Y (model A); 19 in. screen	288	28
Manufacturer Y (model B); 17 in. screen	240	27
Manufacturer Z (model A); 17 in. screen	240	29
Manufacturer Z (model C); 15 in. screen	240	19
Laser printer, typical desktop, small-office type[d]		
Printing speed up to 10 pages per minute	430	137
Printing speed up to 35 pages per minute	890	74
Printing speed up to 19 pages per minute	508	88
Printing speed up to 17 pages per minute	508	98
Printing speed up to 19 pages per minute	635	110
Printing speed up to 24 pages per minute	1344	130
Multifunction (copy, print, scan)[e]		
Small, desktop type	600	30
Medium, desktop type	700	135
Scanner[e]		
Small, desktop type	19	16
Copy machine[f]		
Large, multiuser, office type	1750	800 (idle 260 W)
	1440	550 (idle 135 W)
	1850	1060 (idle 305 W)
Fax machine		
Medium	936	90
Small	40	20
Plotter		
Manufacturer A	400	250
Manufacturer B	456	140

TABLE G.9 Rates of Heat Gain from Office Equipment (*Continued*)

Equipment	Maximum Input Rating, W	Recommended Rate of Heat Gain, W
Vending machines		
Cold food/beverage	72	72
Hot beverage	1150 to 1920	575 to 960
Snack	1725	862
Other	240 to 275	240 to 275
Bar code scanner	440	370
Cash registers	60	48
Check processing workstation	4800	2470
Coffee maker, 10 cups	1500	1050 W sens., 1540 Btu/h latent
Microwave oven, 1 ft^3	600	400
Paper shredder	250 to 3000	200 to 2420
Water cooler, 32 qt/h	700	350

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]Power consumption for newer desktop computers in operational mode varies from 50 to 100 W, but a conservative value of about 65 W may be used. Power consumption in sleep mode is negligible. Because of cooling fan, approximately 90% of load is by convection and 10% is by radiation. Actual power consumption is about 10 to 15% of nameplate value.

[b]Power consumption of laptop computers is relatively small: depending on processor speed and screen size, it varies from about 15 to 40 W. Thus, differentiating between radiative and convective parts of the cooling load is unnecessary and the entire load may be classified as convective. Otherwise, a 75/25% split between convective and radiative components may be used. Actual power consumption for laptops is about 25% of nameplate values.

[c]Flat-panel monitors have replaced cathode ray tube (CRT) monitors in many workplaces, providing better resolution and being much lighter. Power consumption depends on size and resolution, and ranges from about 20 W (for 15 in. size) to 90 W (for 30 in.). The most common sizes in workplaces are 19 and 22 in., for which an average 30 W power consumption value may be used. Use 60/40% split between convective and radiative components. In idle mode, monitors have negligible power consumption. Nameplate values should not be used.

[d]Various laser printers commercially available and commonly used in personal offices were tested for power consumption in print mode, which varied from 75 to 140 W, depending on model, print capacity, and speed. Average power consumption of 110 W may be used. Split between convection and radiation is approximately 70/30%.

[e]Small multifunction (copy, scan, print) systems use about 15 to 30 W; medium-sized ones use about 135 W. Power consumption in idle mode is negligible. Nameplate values do not represent actual power consumption and should not be used. Small, single-sheet scanners consume less than 20 W and do not contribute significantly to building cooling load.

[f]Power consumption for large copy machines in large offices and copy centers ranges from about 550 to 1100 W in copy mode. Consumption in idle mode varies from about 130 to 300 W. Count idle-mode power consumption as mostly convective in cooling load calculations.

G.10 HEAT GAINS FROM APPLIANCES

TABLE G.10 Rate of Heat Gain from Miscellaneous Appliances[a]

Recommended Rates of Radiant and Convective Heat Gain from Unhooded Electric Appliances During Idle (Ready-to-Cook) Conditions

PART A. I-P Units: Btu/h						
	Energy Rate		***Rate of Heat Gain***			
	Rated	**Standby**	**Sensible Radiant**	**Sensible Convective**	**Latent**	**Total**
Cabinet: hot serving (large), insulated	6800	1200	400	800	0	1200
hot serving (large), uninsulated	6800	3500	700	2800	0	3500
proofing (large)	17,400	1400	1200	0	200	1400
proofing (small 15-shelf)	14,300	3900	0	900	3000	3900
Coffee brewing urn	13,000	1200	200	300	700	1200
Drawer warmers, 2-drawer (moist holding)	4100	500	0	0	200	200
Egg cooker	10,900	700	300	400	0	700
Espresso machine	8200	1200	400	800	0	1200
Food warmer: steam table (2-well-type)	5100	3500	300	600	2600	3500
Freezer (small)	2700	1100	500	600	0	1100
Hot dog roller	3400	2400	900	1500	0	2400
Hot plate: single burner, high speed	3800	3000	900	2100	0	3000
Hot-food case (dry holding)	31,100	2500	900	1600	0	2500
Hot-food case (moist holding)	31,100	3300	900	1800	600	3300
Microwave oven: commercial (heavy duty)	10,900	0	0	0	0	0
Oven: countertop conveyorized bake/finishing	20,500	12,600	2200	10,400	0	12,600
Panini	5800	3200	1200	2000	0	3200
Popcorn popper	2000	200	100	100	0	200
Rapid-cook oven (quartz-halogen)	41,000	0	0	0	0	0
Rapid-cook oven (microwave/convection)	24,900	4100	1000	3100	0	1000
Reach-in refrigerator	4800	1200	300	900	0	1200
Refrigerated prep table	2000	900	600	300	0	900
Steamer (bun)	5100	700	600	100	0	700
Toaster: 4-slice pop up (large): cooking	6100	3000	200	1400	1000	2600
contact (vertical)	11,300	5300	2700	2600	0	5300
conveyor (large)	32,800	10,300	3000	7300	0	10,300
small conveyor	5800	3700	400	3300	0	3700
Waffle iron	3100	1200	800	400	0	1200

TABLE G.10 Rate of Heat Gain from Miscellaneous Appliances (*Continued*)

PART A. SI Units: W						
	Energy Rate		*Rate of Heat Gain*			
	Rated	Standby	Sensible Radiant	Sensible Convective	Latent	Total
Cabinet: hot serving (large), insulated	1993	352	117	234	0	352
hot serving (large), uninsulated	1993	1026	205	821	0	1026
proofing (large)	5099	410	352	0	59	410
proofing (small 15-shelf)	4191	1143	0	264	879	1143
Coffee brewing urn	3810	352	59	88	205	352
Drawer warmers, 2-drawer (moist holding)	1202	147	0	0	59	59
Egg cooker	3194	205	88	117	0	205
Espresso machine	2403	352	117	234	0	352
Food warmer: steam table (2-well-type)	1495	1026	88	176	762	1026
Freezer (small)	791	322	147	176	0	322
Hot dog roller	996	703	264	440	0	703
Hot plate: single burner, high speed	1114	879	264	615	0	879
Hot-food case (dry holding)	9115	733	264	469	0	733
Hot-food case (moist holding)	9115	967	264	528	176	967
Microwave oven: commercial (heavy duty)	3194	0	0	0	0	0
Oven: countertop conveyorized bake/finishing	6008	3693	645	3048	0	3693
Panini	1700	938	352	586	0	938
Popcorn popper	586	59	29	29	0	59
Rapid-cook oven (quartz-halogen)	12,016	0	0	0	0	0
Rapid-cook oven (microwave/convection)	7297	1202	293	909	0	293
Reach-in refrigerator	1407	352	88	264	0	352
Refrigerated prep table	586	264	176	88	0	264
Steamer (bun)	1495	205	176	29	0	205
Toaster: 4-slice pop up (large): cooking	1788	879	59	410	293	762
contact (vertical)	3312	1553	791	762	0	1553
conveyor (large)	9613	3019	879	2139	0	3019
small conveyor	1700	1084	117	967	0	1084
Waffle iron	909	352	234	117	0	352

Source: Reprinted with permission; ©ASHRAE, 2013 *ASHRAE Handbook—Fundamentals*.

[a]For residential appliances, see Table 9.3.

For Recommended Rates of Radiant Heat Gain from Hooded Electric Appliances During Idle (Ready-To-Cook) Conditions; Recommended Rates of Radiant Heat Gain from Hooded Gas Appliances During Idle (Ready-To-Cook) Conditions; and Recommended Rates of Radiant and Convective Heat Gain from Warewashing Equipment During Idle (Standby) or Washing Conditions—Refer to 2013 *ASHRAE Handbook—Fundamentals*.

G.11 CLIMATE DATA FOR BUILDING COOLING

TABLE G.11 Cooling Climate Data for Some North American Cities

City, State (or Province)	*I-P Units, CDD50 °F*	*No. Hours 8 A.M.–4 P.M. (°F) 55 < DB < 69 (°C) 13 < DB < 21*	*SI Units CDD10 °C*
Albuquerque, New Mexico	3908	703	2171
Albany, New York	2525	605	1403
Amarillo, Texas	4128	680	2293
Atlanta, Georgia	5038	749	2799
Baltimore, Maryland	3709	NA	2061
Birmingham, Alabama	5206	760	2892
Brownsville, Texas	8777	422	4876
Boise, Idaho	2807	647	1559
Boston, Massachusetts	2897	713	1609
Buffalo, New York	2468	697	1371
Burlington, Vermont	2228	637	1238
Calgary, Alberta	1167	NA	648
Charleston, South Carolina	6188	NA	3438
Cheyenne, Wyoming	1886	608	1048
Chicago, Illinois (O’Hare)	2941	613	1634
Columbia, Missouri	3752	633	2084
Columbus, Ohio	3119	708	1733
Denver, Colorado	2732	739	1518
Detroit, Michigan	3046	NA	1692
Dodge City, Kansas	5001	637	2272
El Paso, Texas	5488	735	3049
Fort Wayne, Indiana	3077	601	1709
Fort Worth, Texas	6557	NA	3643
Fresno, California	5350	785	2972
Great Falls, Montana	1993	641	1107
Honolulu, Hawaii	9949	69	5527
Houston, Texas	7357	NA	4087
Jackson, Mississippi	5900	640	3278
Jacksonville, Florida	6847	674	3804
Lake Charles, Louisiana	6813	668	3785
Las Vegas, Nevada	6745	719	3747
Los Angeles, California	4777	1849	2654
Louisville, Kentucky	4000	636	2222
Lubbock, Texas	4833	743	2685
Madison, Wisconsin	2389	658	1327
Medford, Oregon	2989	749	1661
Memphis, Tennessee	5467	851	3037
Miami, Florida	9474	259	5263
Minneapolis, Minnesota	2680	566	1489
Montreal, Quebec	2146	NA	1192
Nashville, Tennessee	4689	749	2605
New Orleans, Louisiana	6910	789	3893
New York (Central Park), New York	3634	790	2019
Norfolk, Virginia	4478	685	2488
Oklahoma City, Oklahoma	4972	733	2762

TABLE G.11 Cooling Climate Data for Some North American Cities (*Continued*)

City, State (or Province)	*I-P Units, CDD50 °F*	*No. Hours 8 A.M.–4 P.M. (°F) 55 < DB < 69 (°C) 13 < DB < 21*	*SI Units CDD10 °C*
Omaha, Nebraska	3398	586	1888
Ottawa, Ontario	2045	NA	1136
Philadelphia, Pennsylvania	3623	646	2013
Phoenix, Arizona	8425	746	4681
Pittsburgh, Pennsylvania	2836	700	1576
Portland, Maine	1943	665	1079
Portland, Oregon	2517	1060	1398
Raleigh, North Carolina	4499	740	2499
Regina, Saskatchewan	1620	NA	900
Richmond, Virginia	4223	716	2346
Sacramento, California	4474	990	2486
Salt Lake City, Utah	3276	586	1820
San Antonio, Texas	7142	NA	3968
San Diego, California	5223	1911	2902
San Francisco, California	2883	1796	1602
Saint Louis, Missouri	4283	NA	2379
Seattle–Tacoma, Washington	2021	982	1123
Sioux City, Iowa	3149	602	1749
Tampa, Florida	8239	592	4577
Topeka, Kansas	3880	608	2156
Toronto, Ontario	2370	NA	1317
Tucson, Arizona	6921	716	3845
Tulsa, Oklahoma	5150	591	2861
Vancouver, British Columbia	1536	NA	853
Washington, DC	4391	657	2074
Winnipeg, Manitoba	1784	NA	991

Source: Reprinted with permission; ©ASHRAE, ANSI/ASHRAE/IESNA Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

NA = not available

G.12 DESIGN DATA FOR EARTH TUBES

TABLE G.12 Earth Tube Applications[a]

Part A. I-P Units

	Tube			Temperatures (°F)					
Soil, No. of Tubes, Arrangement	**Diameter (in.)**	**Length (ft)**	**Depth[b] (ft)**	**Soil**	**Intake Air[c]**	**Air Velocity (ft/min)**	**Total Flow Rate (ft^3/h)**	**Flow Per Tube (ft^3/h)**	**Peak Sensible Cooling (Btu/h ft)**
Sandy soil; 8 tubes, radial	10	100	8	73°	67–105°	220	57,600	7200	20
Silt loam, wet; 9 tubes, radial (3 trenches)	5	150	8–11.5	73°	62–95°	500	60,000	4000	11
Silt loam; 22 tubes, parallel at 4 ft	10	180	8–9	72°	70–94°	500	359,700	16,350	30
Silt loam; 5 tubes, parallel	12	260	10	63°	60–92°	530	123,600	24,720	40

Part B. SI Units

	Tube			Temperatures (°C)					
Soil, No. of Tubes, Arrangement	**Diameter (cm)**	**Length (m)**	**Depth[b] (m)**	**Soil**	**Intake Air[c]**	**Air Velocity (m/s)**	**Total Flow Rate (m^3/h)**	**Flow Per Tube (m^3/h)**	**Peak Sensible Cooling (W/m)**
Sandy soil; 8 tubes, radial	25	30.5	2.4	23°	19.4–40.6°	1.1	1632	204	19.7
Silt loam, wet; 9 tubes, radial (3 trenches)	13	46	2.4–3.5	23°	16.7–35°	2.5	1080	120	10.6
Silt loam; 22 tubes, parallel at 1.2 m	25	55	2.4–2.7	22°	21.1–34.4°	2.5	10,200	463	29.5
Silt loam; 5 tubes, parallel	30	79	3	17°	15.6–33.3°	2.7	3500	696	38.8

Source: Givoni, B. 1994. *Passive and Low Energy Cooling of Buildings*. Van Nostrand Reinhold, New York. I-P conversions added by the authors of this book.

[a]Central Illinois farm applications, summertime.

[b]Tubes often slope to drain the condensation that occurs as air reaches the dewpoint within the tube.

[c]Intake air temperature range during the period of study.

G.13 PSYCHROMETRIC CHARTS

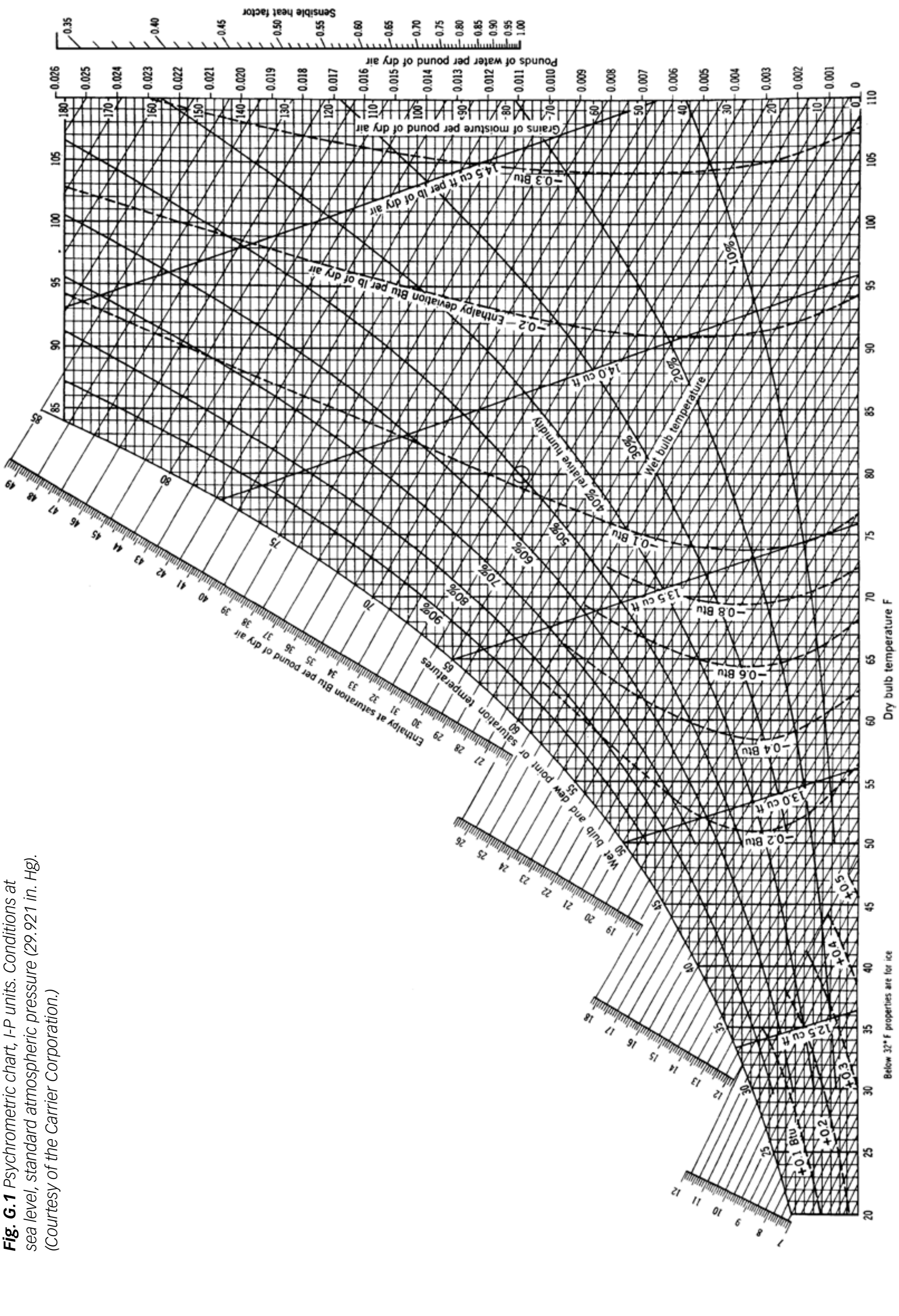
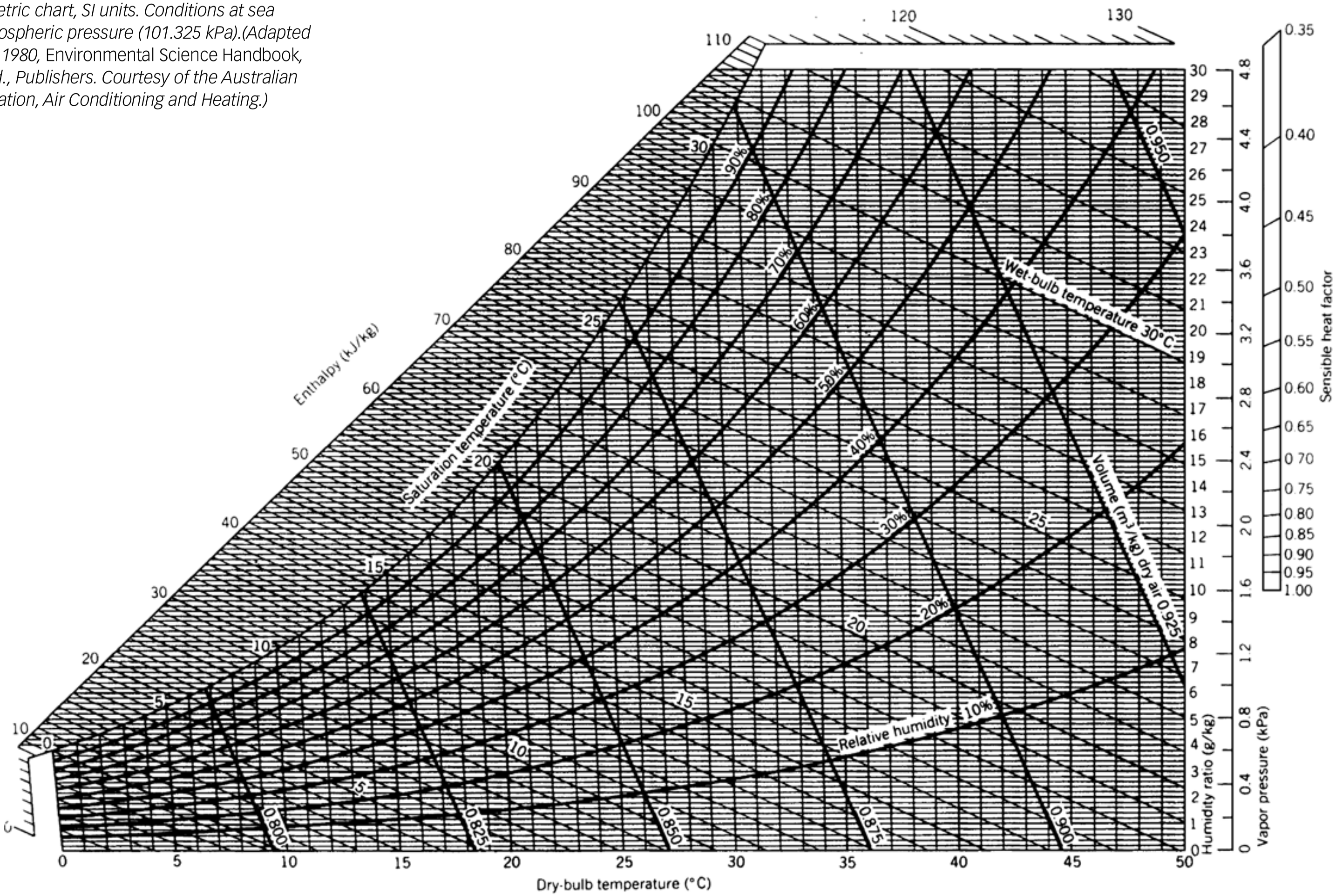


Fig. G.1 Psychrometric chart, I-P units. Conditions at sea level, standard atmospheric pressure (29.921 in. Hg). (Courtesy of the Carrier Corporation.)

Fig. G.2 Psychrometric chart, SI units. Conditions at sea level, standard atmospheric pressure (101.325 kPa).(Adapted from S. V. Szokolay, 1980, Environmental Science Handbook, Longman Group Ltd., Publishers. Courtesy of the Australian Institute of Refrigeration, Air Conditioning and Heating.)



APPENDIX H

Standards/Guidelines for Energy- and Resource-Efficient Building Design

This appendix provides extracts from ASHRAE Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*; ASHRAE's *50% Advanced Energy Design Guide for Small to Medium Office Buildings*; and the U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) rating system for new construction. The purpose of these extracts is to show the general nature of these guidance documents and their formats. Obtain complete information regarding the most current versions of each of these documents from ASHRAE (www.ashrae.org) or USGBC (www.usgbc.org).

H.1 SAMPLE OF PRESCRIPTIVE BUILDING ENVELOPE REQUIREMENTS EXTRACTED FROM ASHRAE STANDARD 90.1-2013: *ENERGY STANDARD FOR BUILDINGS EXCEPT LOW-RISE RESIDENTIAL BUILDINGS*

TABLE H.1 ASHRAE 90.1: Building Envelope Requirements for Climate Zone 5 (I-P Units)

	Nonresidential		***Residential***		***Semiheated***	
Opaque Elements	**Assembly Maximum**	**Insulation Min. R-Value**	**Assembly Maximum**	**Insulation Min. R-Value**	**Assembly Maximum**	**Insulation Min. R-Value**
Roofs						
Insulation entirely above deck	U-0.032	R-30.0 c.i.	U-0.032	R-30.0 c.i.	U-0.063	R-15 c.i.
Metal Building	U-0.037	R-19.0 + R-11.0 Ls or R-25.0 + R-8 Ls	U-0.037	R-19.0 + R-11.0 Ls or R-25.0 + R-8.0 Ls	U-0.082	R-19.0
Attic and Other	U-0.021	R-49.0	U-0.021	R-49.0	U-0.034	R-30.0
Walls, Above-Grade						
Mass	U-0.090	R-11.4 c.i.	U-0.080	R-13.3 c.i.	U-.0151	R-5.7 c.i.
Metal Building	U-0.050	R-0.0 + R-19.0 c.i.	U-0.050	R-0.0 + R-19.0 c.i.	U-0.094	R-0 + R-9.8 c.i.
Steel-Framed	U-0.055	R-13.0 + R-10.0 c.i.	U-0.055	R-13.0 + R-10.0 c.i.	U-0.084	R-13+R-3.8 c.i.
Wood-Framed and Other	U-0.051	R-13 + R-7.5 c.i. or R-19 + R-5 c.i.	U-0.051	R-13 + R-7.5 c.i. or R-19 + R-5 c.i.	U-0.089	R-13.0
Walls, Below-Grade						
Below-Grade Wall	C-0.119	R-7.5 c.i.	C-0.119	R-7.5 c.i.	C-1.140	NR
Floors						
Mass	U-0.057	R-14.6 c.i.	U-0.051	R-16.7 c.i.	U-0.107	R-6.3 c.i.
Steel-Joist	U-0.038	R-30.0	U-0.038	R-30.0	U-0.052	R-19.0
Wood-Framed and Other	U-0.033	R-30.0	U-0.033	R-30.0	U-0.051	R-19.0
Slab-On-Grade Floors						
Unheated	F-0.520	NR	F-0.510	R-20 for 24 in.	F-0.730	NR
Heated	F-0.688	R-20 for 48 in.	F-0.688	R-20 for 24 in.	F-1.020	R-10 for 24 in.
Opaque Doors						
Swinging	U-0.500		U-0.500		U-0.700	
Nonswinging	U-0.500		U-0.500		U-1.450	

TABLE H.1 ASHRAE 90.1: Building Envelope Requirements for Climate Zone 5 (I-P Units) (*Continued*)

	Nonresidential		***Residential***		***Semiheated***	
Fenestration	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**	**Assembly Max. U**	**Assembly Max. SHGC**
Vertical Glazing, 0%–40% of Wall						
Nonmetal framing (all)[a]	U-0.32		U-0.32		U-0.45	
Metal framing (curtainwall/ storefront)[b]	U-0.42		U-0.42		U-0.62	
Metal framing (entrance door)[b]	U-0.50		U-0.50		U-0.70	
Metal framing (all other)[b]	U-0.77	$SHGC_{all}$-0.40	U-0.68	$SHGC_{all}$-0.40	U-0.77	$SHGC_{all}$-0.40
Skylight, 0%-3% of Roof						
All types	U=0.50	SHGC-0.40	U-0.50	SHGC-0.40	U-0.98	$SHGC_{all}$-NR

Source: Reprinted by permission; ©ASHRAE, ANSI/ASHRAE/IESNA Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (I-P Edition).
[a]Nonmetal framing includes framing materials other than metal with or without metal reinforcing or cladding.
[b]Metal framing includes metal framing with or without thermal break. The "all other" subcategory includes operable windows, fixed windows, and non-entrance doors.
NR = no requirement.
c.i. = continuous insulation.

H.2 SAMPLE OF RECOMMENDED BUILDING ENVELOPE REQUIREMENTS EXTRACTED FROM *50% ADVANCED ENERGY DESIGN GUIDE FOR SMALL TO MEDIUM OFFICE BUILDINGS*

TABLE H.2 ***50% Advanced Energy Design Guide for Small to Medium Office Buildings*; Climate Zone 5 Envelope Recommendations**

Item	Component	Recommendation
Roofs	Insulation entirely above deck	R-30.0 c.i.
	Attic and other	R-49.0
	Metal building	R-19.0 + R-11.0 Ls
	SRI	No recommendation
	Mass (HC > 7 Btu/ft^2)	R-13.3 c.i.
	Steel framed	R-13.0 + R-15.6 c.i.
Walls	Wood framed and other	R-13.0 + R-10.0 c.i.
	Metal building	R-0.0 + R-19.0 c.i.
	Below-grade walls	R-7.5 c.i.
	Mass	R-14.6 c.i.
Floors	Steel joist	R-38.0
	Wood framed and other	R-38.0
Slabs	Unheated	R-15.0 for 24 in.
	Heated	R-20.0 for 24 in.
Doors	Swinging	U-0.50
	Nonswinging	U-0.50
Vestibules	At building entrance	Yes
Continuous Air Barriers	Continuous air barrier	Entire building envelope
Vertical Fenestration	WWR	20% to 40%
	Window orientation	Area of W and E windows each less than area of S windows (N in southern hemisphere)
	Exterior sun control (S, E, and W only)	PF-0.5
	Thermal transmittance	Nonmetal framing windows = U-0.35 Metal framing windows = U-0.39
	SHGC	Nonmetal framing windows = 0.26 Metal framing windows = 0.38

Source: Reprinted with permission; ©ASHRAE, *Advanced Energy Design Guide for Small to Medium Office Buildings: Achieving 50% Energy Savings Towards a Net Zero Energy Building*, 2011.

H.3 PROJECT SCORECARD FOR LEED FOR NEW CONSTRUCTION AND MAJOR RENOVATIONS (VERSION 4)

TABLE H.3 LEED for New Construction and Major Renovations; Scorecard (v4)

		POSSIBLE: 1
IPc1	Integrative process	1
LOCATION AND TRANSPORTATION		POSSIBLE: 16
LTc1	LEED for Neighborhood Development location	16
LTc2	Sensitive land protection	1
LTc3	High priority site	2
LTc4	Surrounding density and diverse uses	5
LTc5	Access to quality transit	5
LTc6	Bicycle facilities	1
LTc7	Reduced parking footprint	1
LTc8	Green vehicles	1
SUSTAINABLE SITES		POSSIBLE: 10
SSp1	Construction activity pollution prevention	REQUIRED
SSc1	Site assessment	1
SSc2	Site development — protect or restore habitat	2
SSc3	Open space	1
SSc4	Rainwater management	3
SSc5	Heat island reduction	2
SSc6	Light pollution reduction	1
WATER EFFICIENCY		POSSIBLE: 11
WEp1	Outdoor water use reduction	REQUIRED
WEp2	Indoor water use reduction	REQUIRED
WEp3	Building-level water metering	REQUIRED
WEc1	Outdoor water use reduction	2
WEc2	Indoor water use reduction	6
WEc3	Cooling tower water use	2
WEc4	Water metering	1
ENERGY AND ATMOSPHERE		POSSIBLE: 33
EAp1	Fundamental commissioning and verification	REQUIRED
EAp2	Minimum energy performance	REQUIRED
EAp3	Building-level energy metering	REQUIRED
EAp4	Fundamental refrigerant management	REQUIRED
EAc1	Enhanced commissioning	6
EAc2	Optimize energy performance	18
EAc3	Advanced energy metering	1
EAc4	Demand response	2
EAc5	Renewable energy production	3
EAc6	Enhanced refrigerant management	1
EAc7	Green power and carbon offsets	2

TABLE H.3 LEED for New Construction and Major Renovations; Scorecard (v4) (*Continued*)

MATERIAL AND RESOURCES			POSSIBLE: 13
MRp1	Storage and collection of recyclables		REQUIRED
MRp2	Construction and demolition waste management planning		REQUIRED
MRc1	Building life-cycle impact reduction		5
MRc2	Building product disclosure and optimization — environmental product declarations		2
MRc3	Building product disclosure and optimization — source of raw materials		2
MRc4	Building product disclosure and optimization — material integrations		2
MRc5	Construction and demolition waste management		2
INDOOR ENVIRONMENTAL QUALITY			POSSIBLE: 16
EQp1	Minimum IAQ performance		REQUIRED
EQp2	Environmental tobacco smoke control		REQUIRED
EQc1	Enhanced IAQ strategies		2
EQc2	Low emitting materials		3
EQc3	Construction IAQ management plan		1
EQc4	IAQ assessment		2
EQc5	Thermal comfort		1
EQc6	Interior lighting		2
EQc7	Daylight		3
EQc8	Quality views		1
EQc9	Acoustic performance		1
INNOVATION			POSSIBLE: 6
INc1	Innovation		5
INc2	LEED Accredited Professional		1
REGIONAL PRIORITY			POSSIBLE: 4
RPc1	Regional priority		4
TOTAL			110
40–49 Points	50–59 Points	60–79 Points	80+ Points
CERTIFIED	SILVER	GOLD	PLATINUM

Source: Extracted from LEED http://www.usgbc.org/dopdf.php?q=scorecard/new-construction/v4 (accessed July 2013); used with permission of the U.S. Green Building Council.

APPENDIX I

Annual Solar Performance

There are four parts to this appendix: Tables I.1 through I.3 and Fig. I.1. Table I.3 lists projected performance information for 30 passive solar heating systems (3 water wall, 9 Trombe wall, 9 direct gain, and 9 sunspace) for the U.S. and Canadian locations shown in Fig. C.1. The information is extracted from *Passive Solar Heating Analysis*, which lists a total of 94 systems for about twice as many locations. The specifications for all 94 systems are listed in Table I.1, so the original source may be consulted if a proposed passive system is not reasonably represented by one of those included in this appendix. Figure I.1 illustrates the configurations of the sunspace systems. Table I.2 gives thermal properties for materials commonly used in passive solar buildings.

TABLE I.1 Characteristics of Selected Passive Solar Heating Systems

Part A. **Water Wall Systems**

Designation	Thermal Storage Capacity[a] Btu/ft^2 °F (kJ/m^2 °C)	Wall Thickness in. (mm)	No. of Glazings	Wall Surface	Night Insulation
WW-A1	15.6 (319)	3 (76)	2	Normal	No
WW-A2	31.2 (637)	6 (152)	2	Normal	No
WW-A3[b]	46.8 (956)	9 (229)	2	Normal	No
WW-A4	62.4 (1275)	12 (305)	2	Normal	No
WW-A5	93.6 (1912)	18 (457)	2	Normal	No
WW-A6	124.8 (2550)	24 (610)	2	Normal	No
WW-B1	46.8 (956)	9 (229)	1	Normal	No
WW-B2	46.8 (956)	9 (229)	3	Normal	No
WW-B3	46.8 (956)	9 (229)	1	Normal	Yes
WW-B4[b]	46.8 (956)	9 (229)	2	Normal	Yes
WW-B5	46.8 (956)	9 (229)	3	Normal	Yes
WW-C1	46.8 (956)	9 (229)	1	Selective	No
WW-C2[b]	46.8 (956)	9 (229)	2	Selective	No
WW-C3	46.8 (956)	9 (229)	1	Selective	Yes
WW-C4	46.8 (956)	9 (229)	2	Selective	Yes

Part B. **Trombe Wall Systems: Vented**

Designation	Thermal Storage Capacity[c] Btu/ft^2 °F (kJ/m^2 °C)	Wall Thickness[c] in. (mm)	ρck[d] Btu^2/h ft^4 °F^2	No. of Glazings	Wall Surface	Night Insulation
TW-A1[b]	15 (306)	6 (152)	30	2	Normal	No
TW-A2[b]	22.5 (460)	9 (229)	30	2	Normal	No
TW-A3[b]	30 (613)	12 (305)	30	2	Normal	No
TW-A4[b]	45 (919)	18 (457)	30	2	Normal	No
TW-B1	15 (306)	6 (152)	15	2	Normal	No
TW-B2	22.5 (460)	9 (229)	15	2	Normal	No
TW-B3[b]	30 (613)	12 (305)	15	2	Normal	No
TW-B4	45 (919)	18 (457)	15	2	Normal	No
TW-C1	15 (306)	6 (152)	7.5	2	Normal	No
TW-C2	22.5 (460)	9 (229)	7.5	2	Normal	No
TW-C3	30 (613)	12 (305)	7.5	2	Normal	No
TW-C4	45 (919)	18 (457)	7.5	2	Normal	No
TW-D1	30 (613)	12 (305)	30	1	Normal	No
TW-D2	30 (613)	12 (305)	30	3	Normal	No
TW-D3	30 (613)	12 (305)	30	1	Normal	Yes
TW-D4[b]	30 (613)	12 (305)	30	2	Normal	Yes
TW-D5	30 (613)	12 (305)	30	3	Normal	Yes
TW-E1	30 (613)	12 (305)	30	1	Selective	No
TW-E2[b]	30 (613)	12 (305)	30	2	Selective	No
TW-E3	30 (613)	12 (305)	30	1	Selective	Yes
TW-E4	30 (613)	12 (305)	30	2	Selective	Yes

TABLE I.1 Characteristics of Selected Passive Solar Heating Systems (*Continued*)

Part C. **Trombe Wall Systems: Unvented**

Designation	Thermal Storage Capacity[c] Btu/ft^2 °F (kJ/m^2 °C)	Wall Thickness[c] in. (mm)	ρck[d] Btu^2/h ft^4 °F^2	No. of Glazings	Wall Surface	Night Insulation
TW-F1	15 (306)	6 (152)	30	2	Normal	No
TW-F2	22.5 (460)	9 (229)	30	2	Normal	No
TW-F3[b]	30 (613)	12 (305)	30	2	Normal	No
TW-F4	45 (919)	18 (457)	30	2	Normal	No
TW-G1	15 (306)	6 (152)	15	2	Normal	No
TW-G2	22.5 (460)	9 (229)	15	2	Normal	No
TW-G3	30 (613)	12 (305)	15	2	Normal	No
TW-G4	45 (919)	18 (457)	15	2	Normal	No
TW-H1	15 (306)	6 (152)	7.5	2	Normal	No
TW-H2	22.5 (460)	9 (229)	7.5	2	Normal	No
TW-H3	30 (613)	12 (305)	7.5	2	Normal	No
TW-H4	45 (919)	18 (457)	7.5	2	Normal	No
TW-I1	30 (613)	12 (305)	30	1	Normal	No
TW-I2	30 (613)	12 (305)	30	3	Normal	No
TW-I3	30 (613)	12 (305)	30	1	Normal	Yes
TW-I4	30 (613)	12 (305)	30	2	Normal	Yes
TW-I5	30 (613)	12 (305)	30	3	Normal	Yes
TW-J1	30 (613)	12 (305)	30	1	Selective	No
TW-J2[b]	30 (613)	12 (305)	30	2	Selective	No
TW-J3	30 (613)	12 (305)	30	1	Selective	Yes
TW-J4	30 (613)	12 (305)	30	2	Selective	Yes

Part D. **Direct-Gain Systems**

Designation	Thermal Storage Capacity[c] Btu/ft^2 °F (kJ/m^2 °C)	Mass Thickness[c] in. (mm)	Ratio of Mass to Glazing Area	No. of Glazings	Night Insulation
DG-A1[b]	30 (613)	2 (51)	6	2	No
DG-A2[b]	30 (613)	2 (51)	6	3	No
DG-A3[b]	30 (613)	2 (51)	6	2	Yes
DG-B1[b]	45 (919)	6 (152)	3	2	No
DG-B2[b]	45 (919)	6 (152)	3	3	No
DG-B3[b]	45 (919)	6 (152)	3	2	Yes
DG-C1[b]	60 (1226)	4 (102)	6	2	No
DG-C2[b]	60 (1226)	4 (102)	6	3	No
DG-C3[b]	60 (1226)	4 (102)	6	2	Yes

TABLE I.1 Characteristics of Selected Passive Solar Heating Systems (*Continued*)

Part E. **Sunspace Systems**					
Designation	**Type[e]**	**Tilt (Degrees)**	**Common Wall[f]**	**End Walls[g]**	**Night Insulation**
SS-A1[b]	Attached	50	Masonry	Opaque	No
SS-A2	Attached	50	Masonry	Opaque	Yes
SS-A3	Attached	50	Masonry	Glazed	No
SS-A4	Attached	50	Masonry	Glazed	Yes
SS-A5	Attached	50	Insulated	Opaque	No
SS-A6	Attached	50	Insulated	Opaque	Yes
SS-A7	Attached	50	Insulated	Glazed	No
SS-A8	Attached	50	Insulated	Glazed	Yes
SS-B1[b]	Attached	90/30	Masonry	Opaque	No
SS-B2[b]	Attached	90/30	Masonry	Opaque	Yes
SS-B3[b]	Attached	90/30	Masonry	Glazed	No
SS-B4	Attached	90/30	Masonry	Glazed	Yes
SS-B5	Attached	90/30	Insulated	Opaque	No
SS-B6	Attached	90/30	Insulated	Opaque	Yes
SS-B7	Attached	90/30	Insulated	Glazed	No
SS-B8	Attached	90/30	Insulated	Glazed	Yes
SS-C1[b]	Semi-enclosed	90	Masonry	Common	No
SS-C2[b]	Semi-enclosed	90	Masonry	Common	Yes
SS-C3	Semi-enclosed	90	Insulated	Common	No
SS-C4	Semi-enclosed	90	Insulated	Common	Yes
SS-D1	Semi-enclosed	50	Masonry	Common	No
SS-D2	Semi-enclosed	50	Masonry	Common	Yes
SS-D3	Semi-enclosed	50	Insulated	Common	No
SS-D4	Semi-enclosed	50	Insulated	Common	Yes
SS-E1[b]	Semi-enclosed	90/30	Masonry	Common	No
SS-E2[b]	Semi-enclosed	90/30	Masonry	Common	Yes
SS-E3[b]	Semi-enclosed	90/30	Insulated	Common	No
SS-E4	Semi-enclosed	90/30	Insulated	Common	Yes

Source: Previously adapted, with the permission of ASHRAE, from *Passive Solar Heating Analysis*, by J. D. Balcomb et al, 1984. SI units added by the text authors; not part of the original source.

Note: Vented systems may be made to perform as unvented systems by sealing both top and bottom vent openings.

[a]Per unit of projected area.

[b]Listed in this book.

[c]The thermal storage capacity is per projected area of south aperture (ft^2 of glazing) or, equivalently, the quantity ρct. The wall thickness (t) is listed only as an approximate guide by assuming that $\rho c = 30$ Btu/ft^3 °F (ρ of 150 lb/ft^3 and c of 0.2 Btu/lb °F), typical of ordinary concrete. Example: for DGA1 thermal storage capacity, (30 Btu/ft^3 °F) × (2 in./12 in/ft) × (6 ft^2 of mass/1 ft^2 of glazing) = 30 Btu/ft^2 °F.

[d]ρck is the product of the density (lb/ft^3), specific heat (Btu/lb °F), and thermal conductivity (Btu/h ft °F); see Table I.2.

[e]See Fig. I.1 for additional description.

[f]Common walls should provide closable openings that total at minimum 6% (maximum 15%) of the wall area. Insulated common walls should have minimum R-10 insulation and thermal mass in water at a minimum of 3.8 gal/ft^2 (0.5 ft^3/ft^2) of projected area (155 L/m^2 or 0.15 m^3/m^2). Masonry common walls should have a minimum 3:1 (mass:glass) area ratio.

[g]Opaque end walls are strongly recommended; glazed end walls perform more poorly in most winter climates and are subject to severe summer overheating.

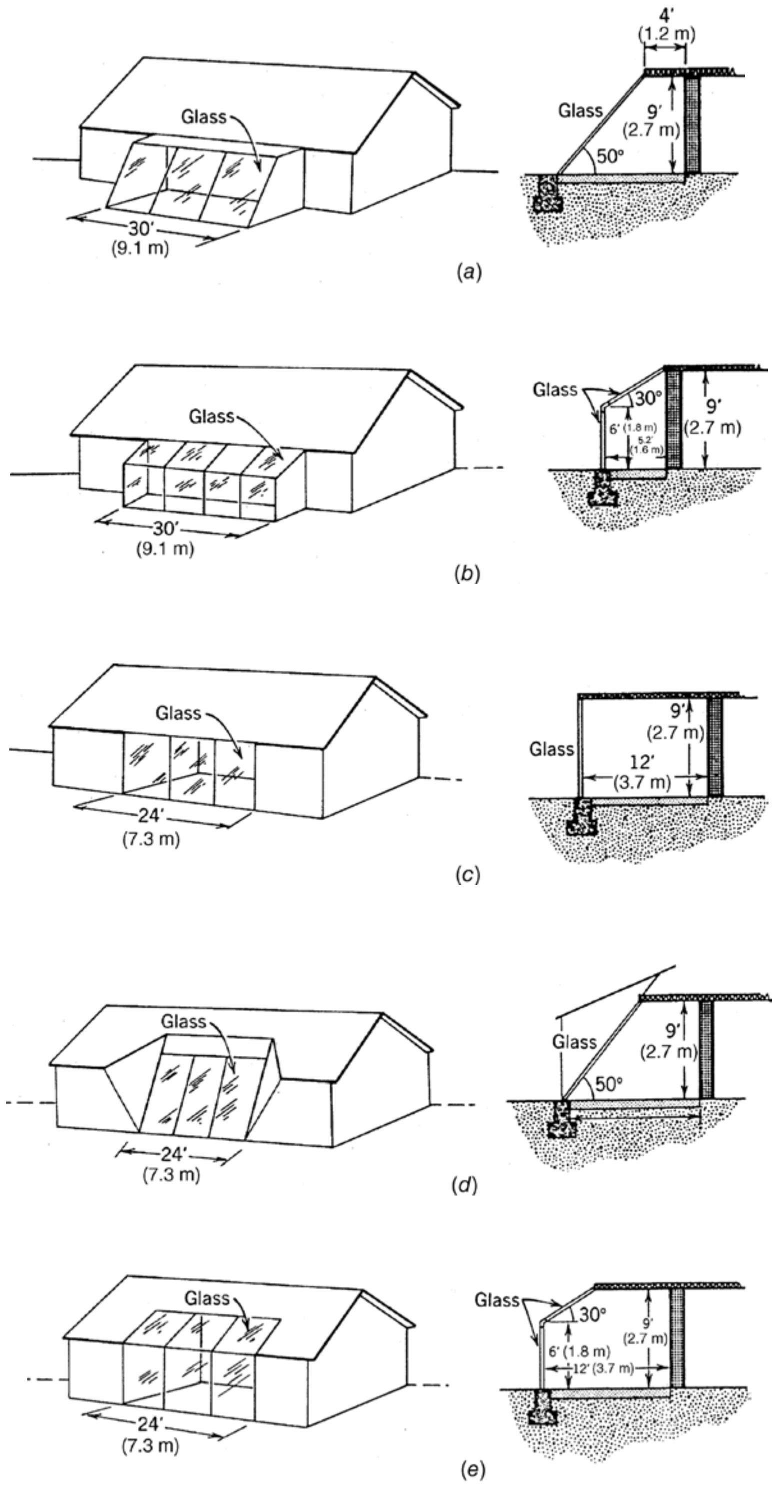


Fig. I.1 *Types of sunspaces, described in Table I.1, Part E. Types (a) and (b) are considered attached to the building; types (c), (d), and (e) are considered semi-enclosed by the building. The architectural detail at the sides of type (d) is insignificant; no shading of the sunspace by the building was accounted for in the performance estimates in Table I.2. (Previously adapted, with the permission of ASHRAE, from* Passive Solar Heating Analysis*, by J. D. Balcomb et al., 1984)*

TABLE I.2 Thermal Properties of Various Materials

Material	Source[a]	Density, ρ lb/ft³ (kg/m³)	Specific Heat, c Btu/lb °F (kJ/kg °C)	Heat Capacity, ρc Btu/ft³ °F (kJ/m³ °C)	Conductivity, k Btu/h °F ft (W/m °C)	Diffusivity, $k/\rho c$ ft²/h (m²/s)	ρck Btu²/h ft⁴ °F² (kJ²/s m⁴ °C²)
Water	1	62.3 (997)	1.0 (4.18)	62.3 (4174)			
Concrete	2,3	144 (2304)	0.21 (0.88)	30.3 (2030)	0.89 (1.54)	0.029 (0.00076)	27.0 (3126)
Concrete block	2,3						
Heavy weight		135 (2160)	0.21 (0.88)	28.4 (1903)	0.74 (1.28)	0.026 (0.00067)	21.0 (2436)
Medium weight		105 (1680)	0.22 (0.92)	23.1 (1548)	0.41 (0.71)	0.018 (0.00046)	9.5 (1099)
Light weight		85 (1360)	0.23 (0.96)	19.6 (1313)	0.27 (0.47)	0.014 (0.00036)	5.3 (617)
Brick	1,4						
Paving		135 (2160)	0.19 (0.80)	25.7 (1722)	0.75 (1.30)	0.029 (0.00075)	19.3 (2239)
Face		130 (2080)	0.19 (0.80)	24.7 (1655)	0.75 (1.30)	0.030 (0.00079)	18.5 (2152)
Building		120 (1920)	0.19 (0.80)	22.8 (1528)	0.42 (0.73)	0.018 (0.00048)	9.6 (1116)
Mortar or grout	1	116 (1856)	0.20 (0.84)	23.2 (1554)	0.42 (0.73)	0.018 (0.00047)	9.7 (1134)
Adobe	5	80 (1280)	0.20 (0.84)	16.0 (1072)	0.38 (0.66)	0.024 (0.00062)	6.1 (708)
		100 (1600)		20.0 (1340)	0.75 (1.30)	0.038 (0.00097)	15.0 (1742)
Gypsum or plasterboard	1	50 (800)	0.26 (1.09)	13.0 (871)	0.097 (0.17)	0.058 (0.0002)	1.3 (148)
Douglas fir plywood	1	34 (544)	0.29 (1.21)	9.9 (663)	0.067 (0.12)	0.007 (0.00018)	0.7 (80)
Hardwood	1	45 (720)	0.30 (1.26)	13.5 (905)	0.092 (0.16)	0.007 (0.00018)	1.2 (145)

Source: Previously adapted, with the permission of ASHRAE, from *Passive Solar Heating Analysis*, by J. D. Balcomb et al, 1984.

Note: Concrete and masonry products can be manufactured in a variety of densities. The values listed are for the most commonly available products. The thermal properties of concrete and concrete block vary with density. Empirical correlations between these properties are [2]$k = 0.05e^{0.02}\rho$ and [3]$c = 1/(3.934 + 0.006\rho)$.

[a]1. ASHRAE 1981 *Handbook—Fundamentals* (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA).

2. "Calculating the Steady State U-Value of Concrete Masonry Walls," Expanded Shale, Clay, and Slate Institute, 4905 Del Ray Avenue, Bethesda, MD.

3. D. Whiting, A. Litvin, and S. E. Goodwin, "Specific Heat of Selected Concretes," *Research and Development Bulletin* RD058.01B, Portland Cement Association, 5420 Old Orchard Road, Skokie, IL.

4. "Brick Passive Solar Heating Systems. Material Properties—Part IV," *Technical Notes on Brick Construction* 43D, Brick Institute of America, 1750 Old Meadow Road, Mc Lean, VA, September/October 1980.

5. Benjamin T. Rogers, private communication; and W. L. Sibbitt, measurements at Los Alamos National Laboratory. Note that the thermal conductivity of adobe varies greatly with moisture content, which is part of the reason for the wide range quoted.

TABLE I.3 Annual Passive Heating Performance: SSF

For each location, degree days listed are DD65F (DD18.3C). For a description of SSF (solar savings fraction) see Fig. 9.3; the LCR (load collector ratio) is described in Section 9.6(f). LCR units are Btu/DDF ft^2 (Wh/DDC m^2).

United States

MONTGOMERY, ALABAMA SSF (%) — 2272 DD65 (1263)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	17	29	38	48	55	64	70	77
WWB4	18	36	48	60	68	78	83	89
WWC2	18	36	47	59	67	76	82	88
TWA1	17	24	29	35	40	46	51	57
TWA2	16	26	33	41	46	54	60	67
TWA3	15	26	34	43	49	58	63	70
TWA4	14	26	34	43	49	58	64	72
TWB3	14	24	31	39	45	54	60	67
TWD4	17	33	43	54	62	72	78	84
TWE2	18	34	44	55	63	72	78	84
TWF3	12	23	30	39	45	54	60	67
TWJ2	15	31	41	52	60	70	76	82
DGA1	12	21	28	34	39	45	49	53
DGA2	13	23	31	39	45	53	58	64
DGA3	15	27	37	47	55	64	70	77
DGB1	12	22	29	37	43	51	56	62
DGB2	13	24	32	41	49	58	65	71
DGB3	15	28	38	49	57	68	75	82
DGC1	14	25	34	43	50	60	66	72
DGC2	15	27	36	47	55	66	72	79
DGC3	18	32	42	55	64	75	81	87
SSA1	21	32	40	48	55	63	68	75
SSB1	17	28	35	42	48	56	62	68
SSB2	21	35	44	54	61	70	76	82
SSB3	17	26	33	40	46	54	59	66
SSC1	15	26	34	43	49	58	64	71
SSC2	17	31	41	51	58	68	74	80
SSE1	20	33	42	51	58	67	72	78
SSE2	23	40	51	62	69	78	83	88
SSE3	18	28	35	43	48	56	62	68

PHOENIX, ARIZONA SSF (%) — 1556 DD65 (865)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	33	54	66	77	83	90	93	96
WWB4	39	64	76	86	91	96	98	99
WWC2	39	63	75	85	90	95	97	99
TWA1	26	40	49	58	65	73	79	84
TWA2	29	46	56	67	74	82	87	91
TWA3	29	48	59	70	77	85	89	93
TWA4	29	48	60	71	78	86	90	94
TWB3	26	44	55	66	73	82	86	91
TWD4	35	58	70	81	87	93	96	98
TWE2	36	59	71	82	88	93	96	98
TWF3	26	44	55	67	74	82	87	92
TWJ2	33	56	68	79	86	92	95	97
DGA1	26	43	54	64	70	77	81	85
DGA2	26	45	56	67	74	82	86	90
DGA3	29	51	64	75	81	87	91	93
DGB1	27	47	60	71	77	84	87	91
DGB2	27	48	61	73	80	88	91	94
DGB3	29	53	67	79	85	91	94	96
DGC1	31	54	58	79	85	90	93	95
DGC2	30	54	68	80	86	92	95	97
DGC3	33	59	74	85	90	95	96	98
SSA1	34	52	62	73	79	86	90	94
SSB1	29	46	56	67	73	81	86	90
SSB2	36	56	67	78	84	90	93	96
SSB3	28	44	54	64	71	79	84	89
SSC1	30	49	61	72	78	86	90	94
SSC2	34	56	68	79	85	91	94	97
SSE1	36	56	67	77	83	90	93	96
SSE2	42	64	76	85	90	95	97	99
SSE3	30	47	57	67	74	82	86	91

TUCSON, ARIZONA SSF (%) — 1758 DD65 (978)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	31	52	64	75	82	89	93	96
WWB4	37	62	75	85	91	96	98	99
WWC2	37	61	74	84	90	95	97	99
TWA1	25	38	47	56	63	72	78	84
TWA2	27	44	55	65	73	81	86	91
TWA3	28	46	58	69	76	84	89	93
TWA4	27	46	58	69	77	85	89	94
TWB3	25	42	53	64	72	81	86	91
TWD4	33	56	69	80	86	93	96	98
TWE2	35	57	70	81	87	93	96	98
TWF3	24	42	53	65	73	81	86	91
TWJ2	31	54	67	78	85	92	95	97
DGA1	24	41	52	62	68	76	80	84
DGA2	24	43	54	65	72	81	85	89
DGA3	27	49	62	74	80	87	90	93
DGB1	24	44	58	69	76	83	87	91
DGB2	25	45	59	72	79	87	91	94
DGB3	27	50	65	78	85	91	94	96
DGC1	28	51	66	78	84	90	93	95
DGC2	28	51	66	79	85	92	95	97
DGC3	31	56	72	84	90	95	96	98
SSA1	33	51	62	72	79	86	90	94
SSB1	29	45	55	66	73	81	86	91
SSB2	35	55	67	77	84	90	94	97
SSB3	27	43	53	64	71	79	84	89
SSC1	28	47	59	70	77	86	90	94
SSC2	32	54	66	78	84	91	94	97
SSE1	35	55	67	77	83	90	93	96
SSE2	41	64	76	85	91	95	97	99
SSE3	30	46	56	67	73	82	86	91

FORT SMITH, ARKANSAS SSF (%) — 3338 DD65 (1856)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	11	21	29	37	43	51	57	64
WWB4	12	27	37	49	57	67	73	80
WWC2	12	27	37	48	55	65	72	79
TWA1	14	19	23	27	31	36	40	45
TWA2	12	20	25	31	36	43	48	54
TWA3	11	19	26	33	38	46	51	58
TWA4	10	19	25	33	38	46	52	59
TWB3	10	18	23	30	35	43	48	54
TWD4	12	25	34	44	51	61	67	75
TWE2	13	26	35	44	52	61	67	75
TWF3	8	16	22	29	34	42	47	54
TWJ2	10	23	32	41	48	58	65	72
DGA1	8	14	19	24	28	33	36	39
DGA2	9	17	23	29	35	42	46	52
DGA3	11	21	28	37	44	53	59	66
DGB1	8	15	19	25	30	36	40	46
DGB2	9	17	23	31	36	45	51	58
DGB3	11	21	29	38	45	56	63	71
DGC1	10	18	24	30	36	44	50	56
DGC2	11	20	27	35	42	52	59	66
DGC3	13	24	32	43	51	63	70	78
SSA1	16	25	31	38	43	50	55	62
SSB1	13	21	26	33	37	44	49	55
SSB2	15	27	35	43	50	59	64	71
SSB3	12	19	25	30	35	41	46	52
SSC1	10	19	25	32	37	45	51	57
SSC2	11	23	31	40	47	56	62	69
SSE1	14	24	31	39	45	53	58	65
SSE2	16	30	39	50	57	66	72	79
SSE3	14	21	27	33	37	44	49	55

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

FRESNO, CALIFORNIA SSF (%) — 2657 DD65 (1477)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	18	31	40	49	56	64	69	75
WWB4	20	38	49	61	68	77	82	87
WWC2	20	38	49	60	67	76	81	86
TWA1	18	26	31	37	41	48	52	58
TWA2	18	28	35	42	48	55	60	67
TWA3	17	28	36	44	50	58	64	70
TWA4	16	28	36	44	51	59	64	71
TWB3	15	26	33	41	47	55	60	67
TWD4	19	35	45	56	63	72	77	83
TWE2	20	36	46	56	63	72	77	83
TWF3	14	25	32	40	47	55	60	66
TWJ2	17	33	43	53	60	69	75	81
DGA1	14	23	30	36	41	47	50	54
DGA2	14	25	33	41	47	54	59	65
DGA3	17	30	39	49	56	65	70	76
DGB1	14	24	31	39	45	52	56	61
DGB2	15	26	35	44	50	59	64	70
DGB3	17	30	40	51	58	68	74	80
DGC1	16	28	37	46	52	60	64	70
DGC2	17	30	39	49	56	65	71	77
DGC3	19	34	45	56	64	74	79	85
SSA1	22	34	41	49	54	61	66	72
SSB1	19	29	36	43	49	56	61	66
SSB2	22	36	45	54	60	69	74	79
SSB3	18	28	34	41	46	53	58	64
SSC1	16	28	36	44	50	59	64	70
SSC2	18	33	42	52	59	68	73	79
SSE1	22	34	42	51	57	64	69	75
SSE2	25	41	51	61	67	75	80	85
SSE3	20	30	36	44	49	56	60	66

SACRAMENTO, CALIFORNIA SSF (%) — 2845 DD65 (1582)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	18	31	39	48	55	63	68	74
WWB4	19	37	49	60	67	76	81	87
WWC2	20	37	48	59	66	75	80	85
TWA1	18	25	30	36	41	47	51	57
TWA2	17	27	34	42	47	55	60	66
TWA3	16	28	35	44	50	58	63	69
TWA4	15	27	35	44	50	58	64	70
TWB3	15	25	32	40	46	54	60	66
TWD4	18	34	44	55	62	71	76	82
TWE2	20	35	45	56	63	71	77	82
TWF3	13	24	32	40	46	54	59	66
TWJ2	17	32	42	53	60	69	74	80
DGA1	13	23	29	36	40	46	49	53
DGA2	14	25	32	40	46	54	58	64
DGA3	16	29	38	48	55	64	69	75
DGB1	13	23	31	39	44	51	55	60
DGB2	14	25	34	43	50	58	64	70
DGB3	16	30	39	50	58	67	73	79
DGC1	16	27	36	45	51	59	63	69
DGC2	16	29	39	49	56	65	70	76
DGC3	19	33	44	56	63	73	79	85
SSA1	22	33	41	48	54	61	65	71
SSB1	19	29	36	43	48	55	60	66
SSB2	22	36	45	54	60	68	73	79
SSB3	18	28	34	41	46	53	57	63
SSC1	16	27	35	44	50	58	63	69
SSC2	18	32	42	51	58	67	72	78
SSE1	21	34	42	50	56	64	68	74
SSE2	24	41	50	60	67	75	79	84
SSE3	20	30	36	43	48	55	60	65

LOS ANGELES, CALIFORNIA SSF (%) — 1793 DD65 (997)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	37	58	70	81	87	93	95	98
WWB4	43	68	80	89	93	97	99	99
WWC2	42	67	79	88	93	97	98	99
TWA1	29	43	52	62	69	77	82	88
TWA2	32	49	60	71	78	86	90	94
TWA3	33	52	63	74	81	88	92	96
TWA4	32	52	64	75	82	89	93	96
TWB3	29	48	59	70	77	85	90	94
TWD4	39	62	74	85	90	95	97	99
TWE2	40	63	75	85	91	95	97	99
TWF3	29	48	59	71	78	86	90	94
TWJ2	37	60	72	83	89	94	97	98
DGA1	29	47	58	68	74	81	85	89
DGA2	29	49	60	71	78	85	89	93
DGA3	32	55	68	79	84	90	93	95
DGB1	30	52	65	76	82	88	91	94
DGB2	30	52	66	78	84	91	94	96
DGB3	33	57	72	83	89	94	96	97
DGC1	34	59	73	84	89	93	95	96
DGC2	34	58	73	84	90	95	97	98
DGC3	37	63	78	89	93	96	97	98
SSA1	41	60	71	80	86	92	95	97
SSB1	35	53	64	74	81	88	91	95
SSB2	42	64	75	84	89	94	97	98
SSB3	34	52	63	73	79	87	90	94
SSC1	33	53	65	76	83	90	93	96
SSC2	38	60	72	83	88	94	96	98
SSE1	43	64	75	84	90	94	97	98
SSE2	50	73	83	91	95	98	99	100
SSE3	36	54	65	75	81	88	92	95

SAN DIEGO, CALIFORNIA SSF (%) — 1512 DD65 (841)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	39	61	73	83	89	94	97	98
WWB4	46	71	83	91	95	98	99	100
WWC2	45	70	82	91	95	98	99	100
TWA1	30	45	55	65	72	80	85	90
TWA2	34	52	64	74	81	88	92	95
TWA3	35	55	67	78	84	91	94	97
TWA4	34	55	67	78	85	91	94	97
TWB3	31	51	62	73	80	88	92	95
TWD4	41	65	77	87	92	96	98	99
TWE2	43	66	78	88	92	97	98	99
TWF3	31	51	63	74	81	89	92	96
TWJ2	39	63	76	86	91	96	98	99
DGA1	31	51	62	72	78	84	88	91
DGA2	31	52	64	74	81	88	91	95
DGA3	34	58	71	81	87	92	94	95
DGB1	32	56	69	79	85	90	93	95
DGB2	32	56	70	81	87	93	95	97
DGB3	35	61	75	86	91	95	96	97
DGC1	37	63	77	87	91	95	96	97
DGC2	36	63	77	87	92	96	98	99
DGC3	39	68	82	91	94	97	98	98
SSA1	43	62	73	82	88	93	95	98
SSB1	37	56	67	77	83	89	93	96
SSB2	45	66	77	86	91	95	97	99
SSB3	36	54	65	75	81	88	92	95
SSC1	36	56	68	79	85	92	95	97
SSC2	40	63	75	85	91	95	97	99
SSE1	45	67	78	86	91	95	97	99
SSE2	52	75	85	92	96	98	99	100
SSE3	38	57	67	77	83	90	93	96

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

SAN FRANCISCO, CALIFORNIA SSF (%)					3050 DD65 (1696)			
Type	**LCR = 200 (1135)**	**100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**
WWA3	24	41	51	62	69	77	82	88
WWB4	27	49	61	73	80	87	91	95
WWC2	27	48	61	72	79	87	91	94
TWA1	21	31	38	46	51	59	64	71
TWA2	22	35	44	53	59	68	73	80
TWA3	21	36	46	56	63	71	77	83
TWA4	20	36	46	56	63	72	78	84
TWB3	19	33	42	52	59	68	73	79
TWD4	25	44	56	67	75	83	87	92
TWE2	26	46	57	68	75	83	88	92
TWF3	18	32	42	52	59	68	73	80
TWJ2	23	42	54	65	73	81	86	91
DGA1	18	31	40	48	54	61	65	69
DGA2	18	33	42	52	59	67	72	78
DGA3	21	38	49	60	68	76	81	86
DGB1	18	33	43	53	60	68	72	77
DGB2	19	34	45	56	64	73	79	84
DGB3	21	39	51	63	72	81	85	90
DGC1	21	38	49	61	68	76	81	85
DGC2	22	39	51	63	71	80	85	89
DGC3	24	43	57	70	78	86	90	94
SSA1	30	45	54	63	68	76	80	85
SSB1	25	39	48	57	63	70	75	81
SSB2	30	47	58	67	74	81	86	90
SSB3	24	38	46	55	61	68	73	79
SSC1	21	37	47	57	64	72	78	84
SSC2	24	42	54	64	72	80	85	90
SSE1	30	47	57	66	72	79	84	88
SSE2	35	54	65	75	81	87	91	94
SSE3	26	40	48	57	63	71	75	81

SANTA MARIA, CALIFORNIA SSF (%)					3061 DD65 (1702)			
Type	**LCR = 200 (1135)**	**100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**
WWA3	25	44	55	67	74	82	87	92
WWB4	29	53	66	78	84	91	95	97
WWC2	29	52	65	77	84	91	94	97
TWA1	21	32	40	49	55	64	69	76
TWA2	22	37	47	57	64	73	79	85
TWA3	22	39	49	60	67	77	82	88
TWA4	22	38	49	61	68	77	83	88
TWB3	20	35	45	56	63	73	78	84
TWD4	27	48	60	72	79	87	91	95
TWE2	28	49	61	73	80	88	92	95
TWF3	19	35	45	56	64	73	79	85
TWJ2	25	46	58	70	77	86	90	94
DGA1	19	34	43	52	59	66	71	75
DGA2	19	35	46	56	64	72	77	83
DGA3	22	40	53	65	73	81	85	89
DGB1	19	35	47	59	66	74	79	83
DGB2	20	37	49	62	70	79	84	89
DGB3	22	41	55	69	77	86	90	93
DGC1	22	41	54	67	75	83	87	90
DGC2	23	42	55	69	77	85	90	93
DGC3	25	47	62	76	83	91	94	96
SSA1	32	49	60	70	76	83	87	92
SSB1	27	43	53	63	70	78	83	88
SSB2	33	52	64	74	80	88	91	95
SSB3	26	41	51	61	68	76	81	86
SSC1	23	40	50	61	69	78	83	89
SSC2	26	46	58	69	77	85	89	94
SSE1	33	52	63	73	80	87	91	94
SSE2	38	61	72	82	88	93	96	98
SSE3	28	43	53	63	70	76	83	88

DENVER, COLORADO SSF (%)						6022 DD65 (3348)		
Type	**LCR = 100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**	**15 (85)**
WWA3	21	29	37	43	52	58	66	75
WWB4	27	38	50	58	68	75	82	89
WWC2	27	37	48	56	67	73	80	88
TWA1	19	23	27	31	37	41	46	53
TWA2	19	25	31	36	44	49	55	64
TWA3	19	26	33	39	47	52	59	69
TWA4	18	25	33	39	47	53	61	70
TWB3	17	23	30	36	43	49	56	65
TWD4	25	34	44	52	62	68	76	85
TWE2	26	35	45	52	62	69	76	85
TWF3	16	22	29	35	43	48	55	65
TWJ2	23	32	42	49	59	66	74	83
DGA1	14	19	25	28	33	37	40	45
DGA2	16	22	30	35	43	47	53	61
DGA3	20	28	37	44	54	61	68	76
DGB1	14	19	25	30	37	42	48	54
DGB2	17	23	31	37	46	52	60	68
DGB3	21	29	38	46	57	65	73	82
DGC1	17	24	31	37	46	52	59	66
DGC2	20	27	36	43	53	60	68	77
DGC3	24	33	43	52	64	72	80	88
SSA1	25	31	38	44	51	56	63	71
SSB1	21	26	33	38	45	50	56	65
SSB2	27	35	44	50	59	65	72	81
SSB3	19	25	31	35	42	46	52	61
SSC1	19	25	33	38	46	52	59	68
SSC2	23	31	41	48	57	63	71	80
SSE1	24	31	39	45	54	59	66	74
SSE2	30	40	50	57	67	73	80	87
SSE3	21	27	33	38	45	49	56	64

GRAND JUNCTION, COLORADO SSF (%)						5607 DD65 (3118)		
Type	**LCR = 100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**	**15 (85)**
WWA3	20	27	35	41	49	55	62	71
WWB4	26	36	47	55	65	71	79	87
WWC2	26	35	46	54	64	70	77	85
TWA1	19	22	26	30	35	38	43	50
TWA2	19	24	30	35	41	46	52	61
TWA3	19	25	31	37	44	49	56	65
TWA4	18	24	31	37	45	50	57	66
TWB3	17	22	29	34	41	46	52	61
TWD4	24	32	42	49	59	65	73	81
TWE2	25	33	43	50	59	66	73	82
TWF3	15	21	28	33	40	45	52	61
TWJ2	22	30	40	47	57	63	70	79
DGA1	14	18	23	26	31	34	37	41
DGA2	16	22	28	33	40	45	50	57
DGA3	20	27	36	42	52	58	65	73
DGB1	14	18	24	28	34	38	43	49
DGB2	16	22	29	35	43	49	56	64
DGB3	20	28	37	44	54	61	69	78
DGC1	17	22	29	34	42	47	53	61
DGC2	19	26	34	41	50	56	64	73
DGC3	23	31	41	49	61	68	76	85
SSA1	24	29	36	41	48	52	58	66
SSB1	20	25	31	35	42	46	52	60
SSB2	25	33	41	47	56	62	68	77
SSB3	18	23	29	33	39	43	48	56
SSC1	18	24	31	36	43	49	55	64
SSC2	22	30	38	45	54	60	67	76
SSE1	23	29	37	42	49	54	61	69
SSE2	28	37	47	54	63	69	75	83
SSE3	20	25	31	35	41	46	51	59

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

HARTFORD, CONNECTICUT SSF (%) — **6354 DD65 (3533)**

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	7	10	13	16	19	22	25	30
WWB4	9	16	23	28	36	41	49	58
WWC2	10	15	22	27	35	40	46	55
TWA1	12	13	14	15	16	17	18	20
TWA2	9	11	13	15	18	20	22	25
TWA3	8	10	13	15	18	21	24	28
TWA4	6	9	12	15	18	21	24	29
TWB3	7	10	12	15	18	20	23	28
TWD4	10	15	21	25	32	37	43	52
TWE2	10	15	21	26	32	37	43	51
TWF3	5	7	10	12	15	17	20	24
TWJ2	8	13	19	23	30	34	40	49
DGA1	4	5	6	6	7	7	6	5
DGA2	7	9	12	14	17	19	22	26
DGA3	10	14	18	22	28	32	37	45
DGB1	4	5	6	6	7	7	7	7
DGB2	7	9	12	15	18	20	23	28
DGB3	10	14	19	23	29	33	39	48
DGC1	5	7	9	10	12	13	14	15
DGC2	9	12	15	18	23	26	30	36
DGC3	12	17	22	27	33	38	45	54
SSA1	13	16	19	21	25	27	30	34
SSB1	11	13	15	17	20	22	25	28
SSB2	14	18	24	27	33	37	43	50
SSB3	10	11	14	15	17	19	21	23
SSC1	6	8	11	13	15	17	20	23
SSC2	8	12	17	21	26	30	35	42
SSE1	10	13	16	18	21	23	26	29
SSE2	13	18	24	29	35	40	45	53
SSE3	11	13	15	17	19	21	23	26

WASHINGTON, DC SSF (%) — **5010 DD65 (2786)**

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	12	16	22	25	31	35	40	48
WWB4	15	23	32	39	48	54	62	72
WWC2	15	23	31	38	46	52	60	69
TWA1	14	16	18	20	23	25	28	32
TWA2	13	16	20	22	27	30	34	40
TWA3	12	15	20	23	28	32	37	43
TWA4	10	14	19	23	29	33	38	45
TWB3	11	14	18	22	27	30	35	42
TWD4	15	21	29	35	43	49	56	65
TWE2	15	22	29	35	43	49	56	65
TWF3	9	12	16	20	25	28	33	40
TWJ2	13	19	27	32	40	46	53	62
DGA1	7	9	12	14	16	17	18	19
DGA2	10	13	18	21	26	29	33	39
DGA3	13	18	25	29	37	42	48	57
DGB1	7	9	12	14	17	19	21	23
DGB2	10	14	18	22	27	31	36	42
DGB3	14	19	25	31	38	44	51	61
DGC1	9	12	16	19	23	25	29	33
DGC2	12	17	22	26	33	37	43	51
DGC3	16	22	29	35	43	50	58	68
SSA1	17	21	26	29	34	38	42	49
SSB1	14	17	21	25	29	32	36	42
SSB2	18	24	31	36	43	48	54	63
SSB3	13	16	20	22	26	29	33	38
SSC1	10	14	18	21	26	30	34	40
SSC2	13	19	25	30	37	42	48	57
SSE1	15	19	24	28	33	37	41	48
SSE2	19	26	34	39	47	53	59	68
SSE3	15	18	22	24	29	31	35	41

MIAMI, FLORIDA SSF (%) — **206 DD65 (115)**

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	82	96	99	100	100	100	100	100
WWB4	89	98	100	100	100	100	100	100
WWC2	88	98	100	100	100	100	100	100
TWA1	64	84	92	97	98	100	100	100
TWA2	73	91	96	99	100	100	100	100
TWA3	76	93	97	99	100	100	100	100
TWA4	76	93	98	99	100	100	100	100
TWB3	71	90	96	99	100	100	100	100
TWD4	84	97	99	100	100	100	100	100
TWE2	85	97	99	100	100	100	100	100
TWF3	72	91	96	99	100	100	100	100
TWJ2	83	96	99	100	100	100	100	100
DGA1	75	92	97	99	100	100	100	100
DGA2	74	92	97	99	100	100	100	100
DGA3	79	93	96	97	97	97	97	97
DGB1	81	95	98	99	99	99	99	99
DGB2	80	96	99	100	100	100	100	100
DGB3	83	96	98	98	98	98	98	98
DGC1	88	97	98	99	99	99	98	98
DGC2	86	98	99	100	100	100	100	100
DGC3	88	98	98	99	99	98	98	98
SSA1	81	95	99	100	100	100	100	100
SSB1	75	92	97	99	100	100	100	100
SSB2	84	97	99	100	100	100	100	100
SSB3	74	92	97	99	100	100	100	100
SSC1	78	94	98	99	100	100	100	100
SSC2	83	96	99	100	100	100	100	100
SSE1	85	97	99	100	100	100	100	100
SSE2	91	99	100	100	100	100	100	100
SSE3	76	93	97	99	100	100	100	100

ORLANDO, FLORIDA SSF (%) — **733 DD65 (408)**

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	45	68	80	89	93	97	98	99
WWB4	52	78	88	95	97	99	100	100
WWC2	52	77	87	94	97	99	100	100
TWA1	34	51	61	72	78	86	90	94
TWA2	38	59	70	80	86	92	95	98
TWA3	40	62	73	83	89	94	97	98
TWA4	39	62	74	84	90	95	97	99
TWB3	36	57	69	80	86	92	95	97
TWD4	47	72	83	91	95	98	99	100
TWE2	49	73	84	92	96	98	99	100
TWF3	36	58	70	80	87	93	95	98
TWJ2	45	70	82	90	94	98	99	100
DGA1	37	58	69	78	84	90	93	95
DGA2	36	59	71	81	86	92	95	97
DGA3	40	66	77	86	90	94	95	96
DGB1	38	64	76	85	90	94	96	97
DGB2	38	64	77	87	92	96	98	99
DGB3	41	69	82	90	94	97	97	98
DGC1	44	72	84	91	94	97	97	98
DGC2	42	71	83	92	95	98	99	100
DGC3	46	76	88	94	96	98	98	98
SSA1	46	67	78	87	92	96	98	99
SSB1	40	61	72	82	88	93	96	98
SSB2	48	71	82	90	94	98	99	100
SSB3	39	59	71	81	86	92	95	98
SSC1	41	63	75	85	90	95	97	99
SSC2	46	70	81	90	94	98	99	100
SSE1	50	72	83	91	95	98	90	100
SSE2	57	80	90	95	98	99	100	100
SSE3	41	62	73	82	88	93	96	98

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

TALLAHASSEE, FLORIDA SSF (%)					1563 DD65 (869)			
Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	24	41	52	63	70	79	84	90
WWB4	27	49	62	74	82	89	93	96
WWC2	27	49	61	73	81	88	92	96
TWA1	21	31	38	46	52	60	65	72
TWA2	22	35	44	53	60	70	75	82
TWA3	22	36	46	56	64	73	79	85
TWA4	21	36	46	57	64	74	79	86
TWB3	19	33	42	52	59	69	75	81
TWD4	25	45	57	69	76	85	89	93
TWE2	26	46	58	69	77	85	90	94
TWF3	18	32	42	52	60	69	75	82
TWJ2	23	42	54	66	74	83	88	92
DGA1	18	31	40	48	54	62	66	71
DGA2	18	33	42	53	60	68	74	79
DGA3	21	37	49	62	69	78	83	87
DGB1	18	32	43	54	61	70	75	80
DGB2	19	34	45	58	66	75	81	86
DGB3	21	38	51	65	73	83	87	92
DGC1	21	38	49	62	71	79	83	88
DGC2	21	38	51	65	73	82	87	91
DGC3	24	43	57	72	80	88	92	95
SSA1	27	42	52	62	69	77	82	88
SSB1	23	36	46	55	62	71	77	83
SSB2	28	45	56	67	74	83	87	92
SSB3	22	35	44	53	60	69	74	81
SSC1	21	37	47	57	65	74	80	86
SSC2	24	42	54	66	73	82	87	92
SSE1	28	45	55	66	73	81	86	91
SSE2	32	53	65	76	83	90	93	96
SSE3	24	37	46	56	63	71	77	83

ATLANTA, GEORGIA SSF (%)					3105 DD65 (1726)			
Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	12	22	29	37	43	52	57	65
WWB4	12	28	38	49	57	67	74	81
WWC2	13	28	38	48	56	66	72	79
TWA1	15	20	24	28	32	37	41	46
TWA2	13	20	26	32	37	44	49	55
TWA3	12	20	26	33	39	47	52	59
TWA4	10	19	26	33	39	47	53	60
TWB3	10	18	24	31	36	43	49	55
TWD4	12	25	35	45	52	61	68	75
TWE2	13	26	35	45	52	62	68	75
TWF3	9	17	23	30	35	43	48	55
TWJ2	11	23	32	42	49	59	65	73
DGA1	9	15	20	25	29	34	37	40
DGA2	10	17	23	30	35	43	47	53
DGA3	12	21	29	38	44	54	60	67
DGB1	9	15	20	26	31	37	42	47
DGB2	10	18	24	32	37	46	52	59
DGB3	12	22	30	39	46	57	64	72
DGC1	10	19	25	32	37	45	50	57
DGC2	11	21	28	36	43	53	59	67
DGC3	13	25	33	44	52	63	71	79
SSA1	17	26	32	40	45	52	57	64
SSB1	14	22	28	34	39	46	51	57
SSB2	16	28	36	45	52	60	66	73
SSB3	13	21	26	32	37	43	48	54
SSC1	11	20	26	33	38	46	51	58
SSC2	12	24	32	41	47	57	63	70
SSE1	15	26	33	41	47	55	60	67
SSE2	17	32	41	51	58	68	74	80
SSE3	15	23	28	34	39	46	51	57

BOISE, IDAHO SSF (%)					5837 DD65 (3245)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	18	23	29	34	40	45	50	57
WWB4	22	31	40	47	56	62	69	77
WWC2	22	30	39	46	54	60	67	75
TWA1	17	20	24	26	30	33	36	41
TWA2	17	21	26	30	35	38	43	49
TWA3	16	21	27	31	37	41	46	53
TWA4	15	21	26	31	37	41	47	54
TWB3	15	20	25	29	35	39	44	50
TWD4	20	28	36	43	51	56	63	71
TWE2	21	29	37	43	51	56	63	71
TWF3	13	18	23	27	33	37	42	49
TWJ2	19	26	34	40	48	54	61	69
DGA1	12	15	19	21	25	26	28	30
DGA2	14	19	24	28	34	38	42	48
DGA3	18	24	32	37	45	50	56	64
DGB1	12	16	20	23	27	29	32	35
DGB2	15	20	26	30	36	40	46	52
DGB3	19	25	33	39	47	52	59	68
DGC1	15	19	25	28	33	37	41	45
DGC2	17	23	30	35	42	47	53	60
DGC3	21	28	37	43	52	58	65	74
SSA1	22	26	32	35	41	44	48	54
SSB1	18	22	27	31	36	39	43	49
SSB2	23	30	37	42	49	54	59	67
SSB3	17	21	25	28	33	36	39	44
SSC1	15	20	26	30	35	39	44	50
SSC2	18	25	33	38	46	51	57	65
SSE1	20	25	31	35	40	44	48	54
SSE2	25	32	40	46	53	58	64	71
SSE3	19	23	27	31	35	38	42	47

CHICAGO, ILLINOIS SSF (%)					6125 DD65 (3406)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	9	13	16	19	23	26	30	35
WWB4	12	19	26	32	40	46	53	62
WWC2	12	18	25	31	38	44	51	60
TWA1	13	14	16	17	19	20	22	24
TWA2	11	13	16	18	21	23	26	30
TWA3	9	12	16	18	22	25	28	33
TWA4	8	11	15	18	22	25	29	34
TWB3	9	11	15	17	21	24	27	32
TWD4	12	17	24	29	36	41	47	56
TWE2	12	18	24	29	36	40	47	55
TWF3	7	9	13	15	19	21	25	29
TWJ2	10	15	22	26	33	38	44	53
DGA1	5	7	8	9	10	10	11	10
DGA2	8	11	14	17	20	23	26	30
DGA3	12	16	21	25	31	35	41	48
DGB1	5	7	8	9	11	11	12	12
DGB2	8	11	15	17	21	24	28	33
DGB3	12	16	22	26	32	37	43	52
DGC1	7	9	12	13	16	17	19	21
DGC2	10	14	18	21	26	30	34	41
DGC3	14	19	25	30	37	42	49	58
SSA1	15	18	21	24	27	30	33	38
SSB1	12	15	18	20	23	25	28	32
SSB2	16	20	26	30	36	40	46	53
SSB3	11	13	16	17	20	22	24	27
SSC1	8	11	14	16	19	21	24	28
SSC2	10	15	20	24	30	34	39	46
SSE1	12	15	18	21	25	27	30	34
SSE2	15	21	27	32	39	43	49	57
SSE3	12	15	17	19	22	24	27	30

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

MOLINE, ILLINOIS SSF (%)					6399 DD65 (3558)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	9	13	16	19	24	26	30	36
WWB4	12	19	26	32	40	46	53	63
WWC2	12	18	25	31	39	44	51	60
TWA1	13	14	16	17	19	20	22	24
TWA2	11	13	16	18	21	23	26	30
TWA3	9	12	16	18	22	25	28	33
TWA4	8	11	15	18	22	25	29	34
TWB3	9	11	15	17	21	24	27	32
TWD4	12	17	24	29	36	41	47	56
TWE2	12	18	24	29	36	41	47	55
TWF3	7	9	13	15	19	21	25	29
TWJ2	10	15	22	26	33	38	44	53
DGA1	5	7	8	9	10	11	11	10
DGA2	8	11	14	17	20	23	26	30
DGA3	12	16	21	25	31	35	41	49
DGB1	5	7	8	9	11	11	12	12
DGB2	8	11	15	17	21	24	28	33
DGB3	12	16	22	26	32	37	43	52
DGC1	7	9	12	13	16	17	19	21
DGC2	10	14	18	21	26	29	34	41
DGC3	14	19	25	30	37	42	49	59
SSA1	15	18	21	24	27	30	33	38
SSB1	12	14	17	20	23	25	28	32
SSB2	15	20	26	30	36	40	46	53
SSB3	11	13	15	17	20	22	24	27
SSC1	8	11	14	16	19	21	24	29
SSC2	10	15	20	24	30	34	39	47
SSE1	12	15	18	21	24	27	30	34
SSE2	15	21	27	32	38	43	49	57
SSE3	12	15	17	19	22	24	27	30

INDIANAPOLIS, INDIANA SSF (%)					5585 DD65 (3105)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	9	12	16	19	22	25	29	34
WWB4	11	18	25	31	39	45	52	61
WWC2	11	18	25	30	37	43	49	58
TWA1	12	14	15	17	18	19	21	23
TWA2	10	13	15	17	20	22	25	29
TWA3	9	12	15	18	21	24	27	31
TWA4	8	11	14	17	21	24	28	33
TWB3	8	11	14	17	20	23	26	31
TWD4	11	17	23	28	35	40	46	55
TWE2	12	17	23	28	35	39	46	54
TWF3	6	9	12	14	18	20	23	28
TWJ2	10	15	21	26	32	37	43	52
DGA1	5	6	8	8	9	10	10	9
DGA2	8	11	14	16	20	22	25	29
DGA3	11	15	20	24	30	34	40	47
DGB1	5	6	8	9	10	10	11	11
DGB2	8	11	14	17	20	23	26	31
DGB3	12	16	21	25	31	36	42	51
DGC1	7	9	11	13	15	16	17	19
DGC2	10	13	17	21	25	28	33	39
DGC3	13	18	24	29	36	41	48	57
SSA1	15	18	21	24	27	30	33	38
SSB1	12	15	17	20	23	25	28	32
SSB2	15	20	26	30	36	40	46	53
SSB3	11	13	16	17	20	22	24	27
SSC1	8	10	13	15	18	20	23	27
SSC2	10	14	19	23	29	33	38	45
SSE1	12	15	18	21	24	27	30	34
SSE2	15	21	27	32	38	43	49	56
SSE3	12	15	17	19	22	24	26	30

SPRINGFIELD, ILLINOIS SSF (%)					5563 DD65 (3093)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	12	16	21	24	30	33	38	45
WWB4	15	23	31	38	46	53	60	70
WWC2	15	22	30	36	45	50	58	67
TWA1	14	16	18	20	22	24	27	30
TWA2	13	16	19	22	26	29	32	38
TWA3	12	15	19	22	27	30	35	41
TWA4	10	14	19	22	27	31	36	43
TWB3	11	14	18	21	26	29	33	39
TWD4	14	21	28	34	42	47	54	63
TWE2	15	21	28	34	42	47	54	63
TWF3	9	12	16	19	24	27	31	37
TWJ2	13	19	26	31	39	44	51	60
DGA1	7	9	11	13	15	16	17	17
DGA2	10	13	17	20	25	28	32	37
DGA3	14	18	24	28	35	40	47	55
DGB1	7	9	12	13	16	17	19	21
DGB2	10	14	18	21	26	29	34	40
DGB3	14	19	25	30	37	42	49	59
DGC1	9	12	15	18	21	23	26	30
DGC2	12	16	21	25	31	35	41	49
DGC3	16	22	28	34	42	48	56	66
SSA1	17	20	25	28	32	36	40	46
SSB1	14	17	21	23	28	30	34	40
SSB2	18	23	29	34	41	46	52	60
SSB3	13	15	19	21	25	27	30	35
SSC1	10	14	17	20	25	28	32	38
SSC2	13	18	24	29	36	40	46	55
SSE1	14	18	23	26	31	34	38	44
SSE2	18	25	32	37	45	50	57	65
SSE3	14	17	21	23	27	29	33	38

SOUTH BEND, INDIANA SSF (%)					6465 DD65 (3595)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	7	9	12	14	16	18	20	23
WWB4	9	14	21	26	33	38	44	52
WWC2	9	14	20	25	31	36	41	49
TWA1	12	12	13	14	15	16	16	17
TWA2	9	11	13	14	16	17	19	21
TWA3	8	10	12	14	16	18	20	23
TWA4	6	9	11	13	16	18	21	24
TWB3	7	9	12	13	16	18	20	23
TWD4	9	14	19	23	29	34	39	47
TWE2	10	14	19	23	29	33	38	45
TWF3	5	7	9	11	13	15	17	20
TWJ2	8	12	17	21	27	31	36	43
DGA1	4	4	5	5	5	5	4	1
DGA2	7	9	11	13	16	17	20	22
DGA3	10	14	18	21	26	29	34	41
DGB1	4	4	5	5	5	5	5	3
DGB2	7	9	12	14	16	18	21	24
DGB3	10	14	19	22	27	31	36	44
DGC1	5	7	8	9	10	10	10	10
DGC2	9	11	15	17	21	23	26	31
DGC3	12	16	21	25	31	35	41	49
SSA1	13	15	18	20	23	25	27	29
SSB1	11	13	15	17	19	20	22	25
SSB2	14	18	23	26	31	35	39	46
SSB3	10	11	13	14	16	17	18	19
SSC1	6	8	10	11	13	14	15	17
SSC2	8	11	15	18	23	26	30	36
SSE1	10	12	15	16	18	20	21	23
SSE2	13	17	23	26	32	36	40	47
SSE3	11	13	15	16	18	19	20	22

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

DES MOINES, IOWA SSF (%) **6718 DD65 (3735)**

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	11	14	19	22	27	30	34	41
WWB4	13	21	29	35	43	49	57	66
WWC2	14	20	28	34	42	47	54	64
TWA1	13	15	17	18	21	22	24	27
TWA2	12	14	17	20	23	26	29	34
TWA3	11	14	17	20	24	27	31	37
TWA4	9	13	17	20	25	28	32	39
TWB3	10	13	16	19	23	26	30	36
TWD4	13	19	26	31	39	44	51	60
TWE2	14	20	26	31	39	44	50	59
TWF3	8	11	14	17	21	24	28	33
TWJ2	11	17	24	29	36	41	48	57
DGA1	6	8	10	11	12	13	14	14
DGA2	9	12	16	18	23	25	29	34
DGA3	13	17	22	27	33	38	44	52
DGB1	6	8	10	11	13	14	15	17
DGB2	9	13	16	19	23	27	31	36
DGB3	13	18	23	28	34	39	46	56
DGC1	8	11	14	15	18	20	22	26
DGC2	11	15	20	23	29	32	38	45
DGC3	15	20	26	31	39	45	52	62
SSA1	16	19	23	25	29	32	36	41
SSB1	13	16	19	21	25	27	31	35
SSB2	16	22	27	32	38	43	48	56
SSB3	12	14	17	19	22	24	27	30
SSC1	9	12	16	18	22	25	28	33
SSC2	12	16	22	26	33	37	43	51
SSE1	13	16	20	23	27	30	34	39
SSE2	16	22	29	34	41	46	52	61
SSE3	13	16	19	21	24	26	29	33

TOPEKA, KANSAS SSF (%) **5243 DD65 (2915)**

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	16	21	27	32	38	43	49	57
WWB4	20	28	38	45	55	61	69	78
WWC2	20	28	37	44	53	60	67	76
TWA1	16	19	22	24	28	31	34	39
TWA2	15	19	24	27	33	36	41	48
TWA3	15	19	24	29	35	39	44	52
TWA4	14	18	24	29	35	40	45	54
TWB3	13	18	23	27	32	36	42	50
TWD4	18	26	34	41	49	55	63	72
TWE2	19	27	35	41	50	55	63	72
TWF3	12	16	21	25	31	35	40	48
TWJ2	17	24	32	38	47	53	60	70
DGA1	10	13	16	19	22	24	26	28
DGA2	13	17	22	26	32	35	40	46
DGA3	16	22	29	34	42	48	55	64
DGB1	10	13	17	19	23	26	29	34
DGB2	13	17	23	27	33	38	43	51
DGB3	17	23	30	36	44	50	58	69
DGC1	13	17	21	25	30	34	38	44
DGC2	15	21	27	32	39	44	51	60
DGC3	19	26	34	40	50	57	65	76
SSA1	20	24	30	33	39	43	48	55
SSB1	16	20	25	29	34	38	42	49
SSB2	21	28	35	40	48	53	60	68
SSB3	15	19	23	26	31	34	38	44
SSC1	14	18	23	27	33	37	43	50
SSC2	17	23	30	36	44	49	56	65
SSE1	18	23	29	33	39	43	49	56
SSE2	23	30	39	45	53	59	66	74
SSE3	17	21	25	29	33	37	41	48

DODGE CITY, KANSAS SSF (%) **5053 DD65 (2810)**

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	21	27	35	41	50	55	63	72
WWB4	26	36	47	55	66	72	80	88
WWC2	26	36	46	54	64	71	78	86
TWA1	19	22	27	30	35	39	44	51
TWA2	19	24	30	35	42	47	53	61
TWA3	19	25	32	37	44	50	57	66
TWA4	18	24	31	37	45	51	58	67
TWB3	17	23	29	34	41	46	53	62
TWD4	24	33	43	50	60	66	74	82
TWE2	25	33	43	50	60	66	74	83
TWF3	16	21	28	33	40	46	52	62
TWJ2	22	30	40	47	57	63	71	80
DGA1	14	18	23	27	31	34	38	42
DGA2	16	22	28	33	41	45	51	58
DGA3	20	27	36	42	52	58	65	74
DGB1	14	18	24	28	35	39	44	50
DGB2	17	22	29	35	44	49	57	65
DGB3	20	28	37	44	55	62	70	79
DGC1	17	22	29	34	42	48	55	62
DGC2	19	26	34	41	51	57	65	74
DGC3	23	31	41	50	61	69	77	86
SSA1	24	30	37	42	49	54	60	68
SSB1	20	25	31	36	43	47	53	62
SSB2	26	33	42	48	57	63	70	78
SSB3	19	24	29	33	40	44	50	57
SSC1	18	24	31	36	44	49	56	65
SSC2	22	30	39	45	55	61	68	77
SSE1	23	30	37	43	51	56	63	71
SSE2	29	38	48	55	64	70	77	85
SSE3	21	26	32	36	42	47	53	61

LEXINGTON, KENTUCKY SSF (%) **4732 DD65 (2631)**

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	12	16	21	25	30	34	39	45
WWB4	15	23	31	38	47	53	60	70
WWC2	15	22	30	37	45	51	58	67
TWA1	14	16	18	20	23	25	27	31
TWA2	13	16	19	22	26	29	33	38
TWA3	12	15	19	23	27	31	35	41
TWA4	11	14	19	23	28	31	36	43
TWB3	11	14	18	21	26	29	34	40
TWD4	15	21	28	34	42	47	54	64
TWE2	15	22	29	34	42	47	54	63
TWF3	9	12	16	19	24	27	32	38
TWJ2	13	19	26	32	39	45	51	61
DGA1	7	9	12	13	15	16	17	18
DGA2	10	14	17	21	25	28	32	37
DGA3	14	19	24	29	36	41	47	55
DGB1	7	10	12	14	16	17	19	21
DGB2	10	14	18	21	26	30	34	40
DGB3	14	19	25	30	37	43	50	59
DGC1	10	13	16	18	21	24	27	31
DGC2	12	17	22	26	31	36	41	49
DGC3	16	22	29	34	42	48	56	66
SSA1	17	21	25	29	34	37	41	47
SSB1	14	18	21	24	29	32	35	41
SSB2	18	24	30	35	42	47	53	61
SSB3	13	16	20	22	26	28	32	36
SSC1	10	14	18	21	25	28	32	38
SSC2	13	18	25	29	36	41	47	55
SSE1	15	19	24	27	32	35	40	46
SSE2	19	26	33	38	46	51	58	66
SSE3	15	18	21	24	28	31	34	39

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

BATON ROUGE, LOUISIANA SSF (%) — 1670 DD65 (929)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	21	35	45	56	63	72	78	84
WWB4	23	43	56	68	75	84	89	93
WWC2	23	43	55	67	74	83	88	92
TWA1	19	28	34	41	46	54	59	65
TWA2	19	31	39	47	54	63	68	75
TWA3	19	32	40	50	57	66	72	79
TWA4	18	31	40	50	57	67	73	79
TWB3	17	29	37	46	53	62	68	75
TWD4	22	39	51	62	70	79	84	90
TWE2	23	40	52	63	70	80	85	90
TWF3	16	28	37	46	53	62	68	75
TWJ2	20	37	48	60	68	77	82	88
DGA1	15	27	34	42	47	54	58	63
DGA2	16	28	37	46	53	61	67	73
DGA3	18	33	43	55	63	72	77	83
DGB1	15	27	36	46	53	62	67	72
DGB2	16	29	39	50	58	68	74	80
DGB3	19	33	45	57	66	76	82	87
DGC1	18	32	42	53	61	71	76	81
DGC2	19	33	44	56	65	75	80	86
DGC3	21	38	50	64	73	83	88	92
SSA1	24	38	47	56	63	71	76	82
SSB1	21	33	41	50	56	65	70	77
SSB2	25	41	51	62	69	77	83	88
SSB3	20	31	39	48	54	63	68	75
SSC1	19	32	41	51	58	67	73	79
SSC2	21	37	48	59	66	76	81	87
SSE1	24	40	49	60	67	75	80	86
SSE2	28	47	59	70	77	85	89	93
SSE3	22	33	41	50	56	65	70	77

SHREVEPORT, LOUISIANA SSF (%) — 2175 DD65 (1209)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	17	30	39	49	56	65	71	78
WWB4	19	38	49	61	69	79	84	90
WWC2	19	37	49	60	68	78	83	89
TWA1	17	25	30	36	41	48	52	58
TWA2	17	27	34	42	48	56	61	68
TWA3	16	27	35	44	50	59	65	72
TWA4	15	27	35	44	51	60	66	73
TWB3	14	25	32	40	47	55	61	68
TWD4	18	34	45	56	63	73	79	85
TWE2	19	35	46	57	64	74	79	86
TWF3	13	24	31	40	46	55	61	68
TWJ2	16	32	42	53	61	71	77	84
DGA1	13	22	29	36	41	47	51	55
DGA2	13	24	32	40	47	55	60	66
DGA3	16	28	38	48	56	66	72	78
DGB1	13	22	30	38	45	53	58	64
DGB2	14	25	33	43	50	60	66	73
DGB3	16	29	39	50	59	70	76	83
DGC1	15	26	35	45	52	62	68	74
DGC2	16	28	38	49	57	68	74	80
DGC3	18	32	44	56	66	77	83	88
SSA1	21	33	41	49	56	64	70	76
SSB1	18	28	35	43	49	58	63	70
SSB2	21	36	45	55	62	71	77	83
SSB3	17	27	34	41	47	55	60	67
SSC1	15	27	35	44	51	60	66	73
SSC2	17	32	42	52	60	69	75	82
SSE1	21	34	43	52	59	68	73	80
SSE2	24	41	52	63	70	79	84	89
SSE3	19	29	36	44	50	58	63	70

NEW ORLEANS, LOUISIANA SSF (%) — 1465 DD65 (815)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	24	41	52	63	70	79	84	89
WWB4	28	50	63	74	81	89	93	96
WWC2	28	49	62	73	80	88	92	95
TWA1	21	31	38	46	52	60	65	72
TWA2	22	35	44	54	60	70	75	81
TWA3	22	36	46	57	64	73	79	85
TWA4	21	36	46	57	64	74	79	85
TWB3	20	33	42	52	60	69	75	81
TWD4	25	45	57	69	76	85	89	93
TWE2	27	46	58	69	77	85	89	94
TWF3	19	33	42	53	60	69	75	82
TWJ2	24	43	55	66	74	83	88	92
DGA1	18	32	40	49	55	62	66	71
DGA2	19	33	43	53	60	68	73	79
DGA3	21	38	50	62	69	78	83	87
DGB1	18	33	43	54	61	70	75	80
DGB2	19	34	45	58	66	75	80	86
DGB3	22	39	51	65	73	83	87	91
DGC1	21	38	50	62	70	79	83	87
DGC2	22	39	51	65	73	82	87	91
DGC3	24	44	57	72	80	88	92	95
SSA1	28	43	52	62	69	78	82	88
SSB1	24	37	46	56	63	72	77	83
SSB2	28	46	57	68	75	83	87	92
SSB3	23	36	44	54	61	69	75	81
SSC1	22	37	47	58	65	74	79	85
SSC2	25	43	54	66	73	82	87	91
SSE1	28	45	55	67	74	82	86	91
SSE2	33	53	66	76	83	90	93	96
SSE3	25	38	47	56	63	72	77	83

PORTLAND, MAINE SSF (%) — 7499 DD65 (4169)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	7	10	13	15	18	21	24	28
WWB4	9	15	22	28	35	41	47	57
WWC2	9	15	21	26	33	38	45	53
TWA1	12	13	14	15	16	17	18	19
TWA2	9	11	13	15	17	19	21	24
TWA3	8	10	13	15	18	20	22	26
TWA4	6	9	12	14	18	20	23	28
TWB3	7	10	12	14	17	19	22	26
TWD4	10	15	20	25	31	36	42	50
TWE2	10	15	21	25	31	35	41	49
TWF3	5	7	10	12	15	17	19	23
TWJ2	8	13	18	22	29	33	39	47
DGA1	4	5	5	6	6	6	6	4
DGA2	7	9	12	14	17	19	21	25
DGA3	10	14	18	22	27	31	36	43
DGB1	4	5	5	6	6	7	6	5
DGB2	7	9	12	14	17	20	22	26
DGB3	11	14	19	23	28	33	38	46
DGC1	5	7	8	10	11	12	13	13
DGC2	9	12	15	18	22	25	29	34
DGC3	12	16	22	26	32	37	43	53
SSA1	13	16	19	21	24	26	29	32
SSB1	11	13	15	17	20	22	24	27
SSB2	14	18	23	27	33	37	42	49
SSB3	10	11	13	15	17	18	20	22
SSC1	6	8	10	12	14	16	18	21
SSC2	8	12	16	20	25	28	33	40
SSE1	10	13	15	17	20	22	24	27
SSE2	13	18	24	28	34	38	44	51
SSE3	11	13	15	17	19	20	22	25

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

BALTIMORE, MARYLAND SSF (%) — 4731 DD65 (2630)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	13	18	24	28	35	39	45	53
WWB4	17	26	35	42	52	58	66	75
WWC2	17	25	34	41	50	56	64	73
TWA1	15	17	20	22	25	28	31	36
TWA2	14	17	21	25	30	33	38	44
TWA3	13	17	22	26	31	35	41	48
TWA4	12	16	22	26	32	36	42	50
TWB3	12	16	20	24	29	33	38	46
TWD4	16	23	31	38	46	52	59	69
TWE2	17	24	32	38	46	52	59	69
TWF3	10	14	19	22	28	32	37	44
TWJ2	14	21	29	35	44	49	57	66
DGA1	8	11	14	16	19	20	22	24
DGA2	11	15	19	23	28	32	37	42
DGA3	15	20	26	32	39	45	52	60
DGB1	8	11	14	17	20	22	25	29
DGB2	11	15	20	24	30	34	40	47
DGB3	15	21	27	33	41	47	55	65
DGC1	11	14	18	22	26	29	34	39
DGC2	13	18	24	29	36	41	47	56
DGC3	17	24	31	37	47	53	62	72
SSA1	18	22	27	31	37	41	46	52
SSB1	15	19	23	27	31	35	40	46
SSB2	19	26	33	38	45	51	57	66
SSB3	14	17	21	24	29	32	36	41
SSC1	12	16	20	24	30	33	38	46
SSC2	15	21	28	33	41	46	52	61
SSE1	16	21	26	31	36	40	46	53
SSE2	21	28	36	42	51	56	63	72
SSE3	16	19	23	26	31	34	38	44

DETROIT, MICHIGAN SSF (%) — 6234 DD65 (3466)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	7	10	13	15	18	20	23	26
WWB4	9	15	22	27	35	40	46	55
WWC2	9	15	21	26	33	38	44	52
TWA1	12	13	14	15	16	16	17	18
TWA2	9	11	13	15	17	19	21	23
TWA3	8	10	13	15	17	19	22	25
TWA4	7	9	12	14	17	20	23	27
TWB3	7	10	12	14	17	19	22	26
TWD4	10	15	20	25	31	35	41	49
TWE2	10	15	20	25	31	35	40	48
TWF3	5	7	10	12	14	16	19	22
TWJ2	8	13	18	22	28	33	38	46
DGA1	4	5	6	6	6	6	5	4
DGA2	7	9	12	14	17	19	21	24
DGA3	10	14	18	22	27	31	36	43
DGB1	4	5	6	6	7	7	6	5
DGB2	7	9	12	14	17	20	22	26
DGB3	11	14	19	23	28	32	38	46
DGC1	5	7	9	10	11	12	12	13
DGC2	9	12	15	18	22	25	28	33
DGC3	12	17	22	26	32	37	43	52
SSA1	13	16	19	21	24	26	28	32
SSB1	11	13	15	17	20	21	24	26
SSB2	14	18	23	27	32	36	41	48
SSB3	10	11	13	15	17	18	20	21
SSC1	6	8	10	12	14	16	18	20
SSC2	8	12	16	20	25	28	32	39
SSE1	10	13	15	17	20	21	23	25
SSE2	13	18	24	28	33	37	43	49
SSE3	11	13	15	17	19	20	22	24

BOSTON, MASSACHUSETTS SSF (%) — 5622 DD65 (3126)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	10	14	18	21	26	29	33	40
WWB4	13	20	28	34	43	49	56	66
WWC2	13	20	27	33	41	47	54	63
TWA1	13	15	16	18	20	21	23	26
TWA2	11	14	17	19	23	25	28	33
TWA3	10	13	17	20	24	27	31	36
TWA4	9	12	16	19	24	27	32	38
TWB3	9	12	16	18	23	26	29	35
TWD4	13	18	25	31	38	43	50	59
TWE2	13	19	26	31	38	43	50	58
TWF3	7	10	14	16	20	23	27	33
TWJ2	11	17	23	28	35	41	47	56
DGA1	6	7	9	10	12	12	13	13
DGA2	9	12	15	18	22	25	28	33
DGA3	12	17	22	26	32	37	43	51
DGB1	6	7	9	11	12	13	14	16
DGB2	9	12	16	18	23	26	30	36
DGB3	13	17	23	27	34	39	46	55
DGC1	8	10	13	15	17	19	22	25
DGC2	11	15	19	23	28	32	37	44
DGC3	14	20	26	31	38	44	51	62
SSA1	15	19	22	25	29	32	36	41
SSB1	13	15	19	21	25	27	31	36
SSB2	16	21	27	32	38	43	48	56
SSB3	11	14	17	19	22	24	27	31
SSC1	9	12	15	17	21	24	27	32
SSC2	11	16	21	26	32	36	42	50
SSE1	13	16	20	23	27	30	34	39
SSE2	16	22	29	34	41	46	52	61
SSE3	13	16	19	21	24	26	29	33

SAULT STE. MARIE, MICHIGAN SSF (%) — 9201 DD65 (5116)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	5	7	8	10	11	12	13	13
WWB4	6	11	17	21	27	31	37	44
WWC2	7	11	16	20	25	29	34	40
TWA1	10	11	11	12	12	12	12	11
TWA2	8	9	10	11	12	13	13	14
TWA3	6	7	9	10	12	13	14	15
TWA4	4	6	8	10	12	13	14	16
TWB3	6	7	9	10	12	13	15	16
TWD4	7	11	16	19	25	28	33	39
TWE2	8	12	16	19	24	27	31	37
TWF3	3	5	6	8	9	10	11	12
TWJ2	6	9	14	17	22	25	30	36
DGA1	2	3	3	2	2	1	0	−4
DGA2	5	7	9	11	13	14	15	17
DGA3	9	12	15	18	23	26	30	35
DGB1	2	2	3	2	2	1	0	−2
DGB2	5	7	9	11	13	14	16	18
DGB3	9	12	16	19	24	27	32	38
DGC1	4	5	5	6	6	6	5	3
DGC2	7	9	12	14	17	19	22	25
DGC3	10	14	19	22	28	31	36	43
SSA1	12	13	15	17	19	20	21	22
SSB1	9	11	12	14	15	16	17	18
SSB2	12	16	20	23	27	30	34	39
SSB3	8	9	11	11	12	13	13	12
SSC1	4	5	7	7	8	8	8	7
SSC2	6	9	12	14	18	20	23	27
SSE1	8	9	11	12	13	13	13	11
SSE2	10	14	18	22	26	29	32	36
SSE3	10	11	12	13	14	15	15	14

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

MINNEAPOLIS, MINNESOTA SSF (%)					8165 DD65 (4540)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	7	9	12	14	17	19	21	24
WWB4	9	14	21	26	33	38	45	54
WWC2	9	14	20	25	32	36	42	50
TWA1	11	12	13	14	15	16	16	17
TWA2	9	11	13	14	16	18	19	21
TWA3	7	10	12	14	16	18	20	23
TWA4	6	8	11	13	16	19	21	25
TWB3	7	9	12	13	16	18	21	24
TWD4	9	14	19	24	30	34	40	48
TWE2	10	14	20	24	29	34	39	46
TWF3	5	7	9	11	13	15	17	20
TWJ2	7	12	17	21	27	31	37	44
DGA1	4	4	5	5	5	5	4	2
DGA2	7	9	11	13	16	18	20	23
DGA3	10	13	18	21	26	30	35	41
DGB1	3	4	5	5	6	5	5	3
DGB2	7	9	12	14	17	19	21	25
DGB3	10	14	19	22	28	31	37	44
DGC1	5	6	8	9	10	11	11	11
DGC2	8	11	15	17	21	24	27	32
DGC3	12	16	21	25	31	36	42	50
SSA1	12	15	17	19	21	23	25	28
SSB1	10	12	14	16	18	19	21	23
SSB2	13	17	22	25	30	34	38	45
SSB3	9	10	12	13	15	16	17	18
SSC1	6	8	10	11	13	14	16	18
SSC2	8	11	15	19	23	27	31	37
SSE1	9	11	13	15	17	18	20	21
SSE2	12	16	21	25	31	34	39	46
SSE3	10	12	14	15	17	18	19	20

MERIDIAN, MISSISSIPPI SSF (%)					2393 DD65 (1331)			
Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	15	28	36	45	52	61	67	74
WWB4	16	34	46	58	66	75	81	87
WWC2	17	34	45	56	64	74	80	86
TWA1	16	23	28	33	38	44	49	54
TWA2	15	24	31	38	44	52	57	64
TWA3	14	25	32	41	47	55	61	68
TWA4	13	24	32	41	47	56	62	69
TWB3	13	22	29	37	43	52	57	64
TWD4	16	31	41	52	60	70	76	82
TWE2	17	32	42	53	60	70	76	83
TWF3	11	21	29	37	43	51	57	64
TWJ2	14	29	39	50	57	67	73	80
DGA1	11	20	26	32	37	43	46	50
DGA2	12	22	29	37	43	51	56	62
DGA3	14	26	35	45	52	62	68	75
DGB1	11	20	27	34	40	48	53	59
DGB2	12	22	30	39	46	56	62	69
DGB3	14	26	36	46	55	66	72	80
DGC1	13	24	31	41	47	57	63	69
DGC2	14	26	34	45	52	63	69	76
DGC3	16	30	40	52	61	73	79	86
SSA1	20	31	38	46	52	61	66	72
SSB1	16	26	33	41	46	54	59	66
SSB2	20	33	42	52	59	68	74	80
SSB3	16	25	31	39	44	52	57	63
SSC1	14	24	32	41	47	55	61	68
SSC2	15	29	38	49	56	65	71	78
SSE1	19	31	40	49	55	64	70	76
SSE2	22	38	49	60	67	76	81	87
SSE3	17	27	33	41	46	54	59	66

SAINT LOUIS, MISSOURI SSF (%)					4754 DD65 (2643)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	15	20	26	30	36	41	47	55
WWB4	19	27	37	44	53	59	67	76
WWC2	19	27	36	42	51	57	65	74
TWA1	16	18	21	23	27	29	32	37
TWA2	15	19	23	26	31	35	39	46
TWA3	14	18	23	27	33	37	42	50
TWA4	13	18	23	27	33	38	43	51
TWB3	13	17	22	25	31	35	40	47
TWD4	18	25	33	39	48	53	61	70
TWE2	18	26	33	39	48	53	61	70
TWF3	11	15	20	24	29	33	38	46
TWJ2	16	23	31	37	45	51	58	67
DGA1	9	12	15	18	20	22	24	26
DGA2	12	16	21	25	30	34	38	44
DGA3	16	21	28	33	41	46	53	62
DGB1	10	13	16	18	22	24	27	31
DGB2	12	17	22	26	32	36	41	49
DGB3	16	22	29	34	43	48	56	66
DGC1	12	16	20	23	28	31	35	41
DGC2	15	20	26	30	37	42	49	57
DGC3	19	25	33	39	48	54	63	73
SSA1	19	24	29	32	38	42	47	53
SSB1	16	20	24	28	33	36	41	47
SSB2	21	27	34	39	46	52	58	67
SSB3	15	18	22	25	30	33	37	43
SSC1	13	17	22	26	31	35	40	47
SSC2	16	22	29	34	42	47	54	63
SSE1	18	22	28	32	38	42	47	54
SSE2	22	29	37	43	52	57	64	73
SSE3	17	20	24	28	32	35	40	46

SPRINGFIELD, MISSOURI SSF (%)					4571 DD65 (2542)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	16	22	28	33	40	45	52	60
WWB4	21	30	40	47	57	63	71	80
WWC2	21	29	39	46	55	62	69	78
TWA1	17	19	23	25	29	32	36	41
TWA2	16	20	25	29	34	38	43	51
TWA3	15	20	26	30	36	41	46	55
TWA4	14	19	25	30	37	41	48	56
TWB3	14	18	24	28	34	38	44	52
TWD4	19	27	36	42	51	57	65	74
TWE2	20	28	36	43	51	57	65	74
TWF3	12	17	22	26	33	37	43	51
TWJ2	18	25	33	40	49	55	62	72
DGA1	11	14	18	20	24	26	28	30
DGA2	13	18	23	27	33	37	42	48
DGA3	17	23	30	36	44	50	57	66
DGB1	11	14	18	21	25	28	32	37
DGB2	14	18	24	28	35	39	46	54
DGB3	17	24	31	37	46	52	60	71
DGC1	13	18	22	26	32	36	41	47
DGC2	10	21	28	33	41	46	54	63
DGC3	20	27	35	42	52	59	67	78
SSA1	21	26	31	36	42	46	51	59
SSB1	17	22	27	30	36	40	45	52
SSB2	22	29	37	42	50	55	62	71
SSB3	16	20	25	28	33	37	41	48
SSC1	14	19	25	29	35	39	45	53
SSC2	18	24	32	38	46	51	58	68
SSE1	19	25	31	36	42	47	52	60
SSE2	24	32	41	47	56	62	69	77
SSE3	18	22	27	30	36	39	44	51

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

HELENA, MONTANA SSF (%)						8197 DD65 (4558)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	11	14	19	22	27	30	34	39
WWB4	14	21	29	35	43	49	55	64
WWC2	14	20	28	34	41	47	53	62
TWA1	13	15	17	19	21	22	24	27
TWA2	12	14	18	20	24	26	29	33
TWA3	11	14	18	20	25	28	31	36
TWA4	9	13	17	20	25	28	32	38
TWB3	10	13	16	19	23	26	30	35
TWD4	13	19	26	31	39	44	50	58
TWE2	14	20	26	31	39	43	49	57
TWF3	8	11	14	17	21	24	28	33
TWJ2	12	17	24	29	36	41	47	55
DGA1	6	8	10	11	13	13	14	14
DGA2	9	12	16	19	23	26	29	33
DGA3	13	17	23	27	34	38	44	51
DGB1	6	8	10	12	14	15	16	17
DGB2	9	13	17	20	24	27	31	37
DGB3	13	18	24	28	35	40	46	55
DGC1	8	11	14	16	19	21	23	26
DGC2	11	15	20	24	30	33	38	44
DGC3	15	20	27	32	40	45	52	61
SSA1	16	19	23	25	29	32	35	39
SSB1	13	16	19	21	25	27	30	34
SSB2	17	22	27	32	38	42	47	54
SSB3	12	14	17	19	22	24	26	29
SSC1	9	12	16	18	22	25	28	32
SSC2	12	17	22	27	33	37	42	49
SSE1	13	17	20	23	27	29	32	35
SSE2	17	23	29	34	40	45	50	57
SSE3	13	16	19	21	24	26	29	32

OMAHA, NEBRASKA SSF (%)						6606 DD65 (3673)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	12	16	21	24	30	33	38	45
WWB4	15	22	31	37	47	53	60	70
WWC2	15	22	30	36	45	51	58	68
TWA1	14	16	18	20	22	24	27	30
TWA2	13	15	19	22	26	29	32	38
TWA3	11	15	19	22	27	30	35	41
TWA4	10	14	19	22	27	31	36	43
TWB3	11	14	18	21	25	29	33	40
TWD4	14	21	28	34	42	47	54	64
TWE2	15	21	28	34	42	47	54	63
TWF3	9	12	16	19	24	27	31	37
TWJ2	13	19	26	31	39	49	51	61
DGA1	7	9	11	13	15	16	17	17
DGA2	10	13	17	20	25	28	32	37
DGA3	13	18	24	28	35	40	47	55
DGB1	7	9	11	13	15	17	19	21
DGB2	10	14	18	21	26	29	34	40
DGB3	14	19	25	29	37	42	49	59
DGC1	9	12	15	18	21	23	26	30
DGC2	12	16	21	25	31	35	41	49
DGC3	16	21	28	33	42	48	56	66
SSA1	16	20	24	27	32	35	39	45
SSB1	14	17	20	23	27	30	34	39
SSB2	18	23	29	34	40	45	51	59
SSB3	12	15	18	21	24	26	29	34
SSC1	10	13	17	20	25	28	32	38
SSC2	13	18	29	29	36	40	47	55
SSE1	14	18	22	25	30	33	37	40
SSE2	18	24	31	37	44	49	56	65
SSE3	14	17	20	23	26	29	32	37

ELY, NEVADA SSF (%)						7818 DD65 (4347)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	18	24	32	37	46	51	58	67
WWB4	23	33	44	52	62	69	76	85
WWC2	23	32	43	50	60	67	75	83
TWA1	17	20	24	29	32	35	40	47
TWA2	17	21	27	31	38	43	49	57
TWA3	16	22	28	33	41	46	52	61
TWA4	15	21	28	33	41	46	53	63
TWB3	15	20	26	31	38	43	49	58
TWD4	21	29	39	46	56	62	70	79
TWE2	22	30	40	47	56	63	70	79
TWF3	13	18	25	29	37	42	48	57
TWJ2	19	27	37	44	53	60	68	77
DGA1	11	15	20	23	27	30	33	37
DGA2	14	19	25	30	37	41	47	54
DGA3	18	24	32	39	48	55	62	71
DGB1	11	15	20	24	30	34	39	45
DGB2	14	19	26	31	39	45	52	61
DGB3	18	25	33	40	51	58	66	76
DGC1	14	19	25	30	38	43	49	57
DGC2	17	23	31	37	46	53	60	70
DGC3	21	29	38	46	57	65	74	83
SSA1	23	29	36	40	48	52	58	66
SSB1	19	24	30	34	41	46	51	59
SSB2	25	32	41	47	55	61	68	76
SSB3	18	22	28	32	38	42	48	55
SSC1	16	21	27	32	40	45	51	60
SSC2	19	27	35	42	51	57	64	74
SSE1	22	28	36	41	49	54	60	68
SSE2	27	37	46	53	62	68	75	83
SSE3	20	24	30	34	41	45	51	58

RENO, NEVADA SSF (%)						6027 DD65 (3351)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	25	33	41	48	57	63	70	78
WWB4	31	42	54	62	72	78	84	91
WWC2	31	41	53	60	70	76	83	90
TWA1	21	25	30	35	41	45	50	58
TWA2	22	28	35	40	48	53	60	69
TWA3	22	29	37	43	51	57	64	73
TWA4	21	29	37	43	52	58	65	74
TWB3	20	26	34	40	48	53	60	69
TWD4	28	38	48	56	66	72	79	87
TWE2	29	39	49	57	66	72	79	87
TWF3	19	25	33	39	47	53	60	69
TWJ2	26	36	46	54	64	70	77	85
DGA1	17	23	29	33	38	42	46	50
DGA2	19	26	34	39	47	52	58	65
DGA3	23	32	41	49	58	64	71	79
DGB1	17	23	30	36	43	48	53	60
DGB2	20	27	35	42	51	57	64	72
DGB3	24	32	43	51	62	69	76	84
DGC1	21	28	36	43	52	57	64	71
DGC2	23	31	41	48	59	65	72	80
DGC3	27	37	48	57	69	75	83	89
SSA1	29	36	43	49	56	61	67	75
SSB1	24	30	37	43	50	55	61	69
SSB2	31	39	48	55	64	69	76	83
SSB3	23	29	35	40	47	52	58	65
SSC1	22	29	37	43	51	57	64	73
SSC2	26	35	45	52	61	67	75	83
SSE1	29	36	45	51	59	64	70	78
SSE2	35	45	55	62	71	76	82	89
SSE3	25	31	38	43	50	55	61	68

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

LAS VEGAS, NEVADA SSF (%)						**2602 DD65 (1447)**		
Type	**LCR = 200 (1135)**	**100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**
WWA3	24	41	52	63	71	80	85	90
WWB4	28	50	63	75	82	89	93	96
WWC2	28	49	62	74	81	88	92	96
TWA1	21	31	38	46	52	61	66	73
TWA2	22	35	44	54	61	70	76	82
TWA3	22	37	47	57	64	74	79	85
TWA4	21	36	47	58	64	74	80	86
TWB3	19	33	43	53	60	69	75	82
TWD4	25	45	57	69	77	85	89	93
TWE2	27	46	58	70	77	85	90	94
TWF3	18	33	43	53	60	70	76	82
TWJ2	24	43	55	67	75	83	88	92
DGA1	18	32	40	49	55	63	67	72
DGA2	18	33	43	53	60	69	74	80
DGA3	21	38	50	62	70	78	83	88
DGB1	18	33	44	55	62	71	75	80
DGB2	19	35	46	58	67	76	81	86
DGB3	21	39	52	65	74	83	87	92
DGC1	21	38	51	63	71	79	84	88
DGC2	21	39	52	65	74	83	87	91
DGC3	24	44	58	72	80	88	92	95
SSA1	26	40	50	59	66	74	79	85
SSB1	22	35	44	53	60	69	74	80
SSB2	27	44	54	65	72	81	85	90
SSB3	21	34	42	51	57	66	71	78
SSC1	22	37	47	58	65	75	80	86
SSC2	24	43	55	66	73	82	87	92
SSE1	27	43	53	64	71	79	84	89
SSE2	31	51	63	74	80	88	91	95
SSE3	23	36	45	54	60	69	74	80

LOS ALAMOS, NEW MEXICO SSF (%)						**6437 DD65 (3579)**		
Type	**LCR = 100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**	**15 (85)**
WWA3	20	27	35	41	49	55	62	72
WWB4	25	36	47	55	66	72	80	88
WWC2	25	35	46	54	64	71	78	86
TWA1	18	22	26	29	34	38	43	50
TWA2	18	23	29	34	41	46	52	61
TWA3	18	24	31	36	44	49	56	66
TWA4	17	23	31	36	45	50	57	67
TWB3	16	22	28	33	41	46	53	62
TWD4	23	32	42	49	59	66	74	83
TWE2	24	33	43	50	60	66	74	83
TWF3	15	20	27	32	40	45	52	62
TWJ2	21	30	40	47	57	63	71	80
DGA1	13	17	22	26	31	34	37	41
DGA2	15	21	28	33	40	45	50	58
DGA3	19	26	35	42	52	58	65	74
DGB1	13	18	23	27	34	38	44	50
DGB2	16	21	28	34	43	49	56	65
DGB3	20	27	36	43	54	62	70	80
DGC1	16	22	28	34	42	48	55	63
DGC2	18	25	33	40	50	57	65	74
DGC3	22	31	41	49	61	69	77	86
SSA1	25	31	38	44	51	56	63	71
SSB1	21	26	32	37	44	49	56	64
SSB2	27	34	43	50	59	65	72	80
SSB3	19	24	30	35	42	46	52	60
SSC1	17	23	30	36	43	49	56	65
SSC2	21	29	38	45	54	61	68	78
SSE1	24	31	39	45	53	59	65	74
SSE2	30	39	50	57	67	73	79	87
SSE3	21	27	33	37	44	49	55	63

ALBUQUERQUE, NEW MEXICO SSF (%)						**4293 DD65 (2387)**		
Type	**LCR = 100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**	**15 (85)**
WWA3	28	37	46	54	63	69	76	85
WWB4	35	47	59	67	77	83	89	94
WWC2	34	46	58	66	76	82	88	94
TWA1	22	27	33	38	45	50	56	64
TWA2	24	31	39	45	53	59	66	75
TWA3	25	32	41	48	57	63	70	79
TWA4	24	32	41	48	58	64	71	80
TWB3	22	29	38	44	53	59	66	75
TWD4	31	42	53	61	71	77	84	91
TWE2	32	43	54	62	72	78	84	91
TWF3	21	29	37	44	53	59	66	76
TWJ2	29	40	51	59	69	75	82	90
DGA1	19	26	33	37	44	48	52	58
DGA2	21	29	38	44	52	57	64	71
DGA3	25	35	46	54	64	70	76	84
DGB1	20	27	35	41	50	55	61	68
DGB2	22	30	40	47	58	64	71	79
DGB3	26	36	47	56	68	75	82	89
DGC1	23	32	42	49	60	66	72	79
DGC2	25	34	46	54	65	72	79	86
DGC3	30	40	53	63	75	82	88	93
SSA1	30	38	46	52	61	66	73	81
SSB1	25	32	40	46	54	60	67	75
SSB2	32	42	52	59	68	74	81	88
SSB3	24	30	38	43	51	57	63	72
SSC1	24	32	41	48	57	63	71	79
SSC2	29	39	50	57	67	73	80	88
SSE1	31	39	49	55	64	70	77	85
SSE2	38	49	60	67	76	82	88	93
SSE3	26	33	40	46	54	60	66	75

ALBANY, NEW YORK SSF (%)						**6891 DD65 (3831)**		
Type	**LCR = 100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**	**15 (85)**
WWA3	7	9	12	14	17	18	21	24
WWB4	8	14	21	26	33	38	45	54
WWC2	9	14	20	25	31	36	42	51
TWA1	11	12	13	14	15	15	16	17
TWA2	9	10	12	14	16	17	19	21
TWA3	7	9	12	13	16	18	20	23
TWA4	6	8	11	13	16	18	21	25
TWB3	7	9	11	13	16	18	20	24
TWD4	9	13	19	23	30	34	40	48
TWE2	9	14	19	23	29	33	39	46
TWF3	5	7	9	11	13	15	17	20
TWJ2	7	12	17	21	27	31	37	45
DGA1	3	4	5	5	5	4	4	2
DGA2	6	8	11	13	15	17	20	23
DGA3	10	13	17	21	26	29	34	41
DGB1	3	4	4	5	5	5	4	3
DGB2	6	9	11	13	16	18	21	24
DGB3	10	14	18	22	27	31	36	44
DGC1	5	6	7	8	10	10	10	10
DGC2	8	11	14	17	20	23	27	32
DGC3	12	16	21	25	31	35	41	50
SSA1	12	15	17	19	22	24	27	30
SSB1	10	12	14	16	18	20	22	25
SSB2	13	17	22	26	31	35	39	46
SSB3	9	11	12	14	15	16	18	19
SSC1	6	7	9	11	13	14	16	18
SSC2	7	11	15	18	23	26	31	37
SSE1	9	11	14	16	18	20	21	23
SSE2	12	17	22	26	32	36	41	48
SSE3	11	12	14	16	17	19	20	22

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

BUFFALO, NEW YORK SSF (%) — 6931 DD65 (3854)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	5	6	8	9	11	11	12	13
WWB4	6	11	16	21	27	31	37	44
WWC2	6	11	16	19	25	29	34	41
TWA1	10	11	11	12	12	12	11	11
TWA2	8	9	10	11	12	12	13	13
TWA3	6	7	9	10	11	12	13	14
TWA4	4	6	8	9	11	12	14	16
TWB3	6	7	9	10	12	13	14	16
TWD4	7	11	15	19	24	28	32	39
TWE2	8	11	15	19	23	27	31	37
TWF3	3	5	6	7	9	10	11	12
TWJ2	5	9	13	17	22	25	29	36
DGA1	2	2	2	2	1	0	–1	–4
DGA2	5	7	9	10	12	13	14	16
DGA3	9	12	15	18	22	25	29	34
DGB1	2	2	2	2	1	0	0	–4
DGB2	5	7	9	10	12	14	15	17
DGB3	9	12	16	19	23	27	31	37
DGC1	4	4	5	5	5	5	4	2
DGC2	7	9	12	14	16	18	21	24
DGC3	10	14	18	22	27	31	35	42
SSA1	11	13	15	17	19	20	21	22
SSB1	9	11	12	13	15	16	17	18
SSB2	12	15	19	23	27	30	34	40
SSB3	8	9	11	11	12	13	13	13
SSC1	4	5	6	7	8	8	8	7
SSC2	6	8	12	14	17	20	23	27
SSE1	8	9	11	12	13	13	14	13
SSE2	10	14	18	22	26	29	33	38
SSE3	10	11	12	13	14	15	15	15

SYRACUSE, NEW YORK SSF (%) — 6681 DD65 (3715)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	5	7	9	10	12	13	14	15
WWB4	6	12	17	22	28	33	38	46
WWC2	7	11	17	21	26	30	36	43
TWA1	11	11	12	12	12	13	12	12
TWA2	8	9	10	11	13	13	14	15
TWA3	6	8	9	11	12	14	15	16
TWA4	5	7	9	10	12	14	15	18
TWB3	6	7	9	11	13	14	16	18
TWD4	7	11	16	20	25	29	34	41
TWE2	8	12	16	20	25	28	33	39
TWF3	4	5	7	8	10	11	12	13
TWJ2	6	10	14	18	23	26	31	38
DGA1	2	3	3	3	2	1	0	–3
DGA2	6	7	9	11	13	14	16	17
DGA3	9	12	16	18	23	26	30	36
DGB1	2	3	3	3	2	1	0	–2
DGB2	6	7	9	11	13	15	16	19
DGB3	9	12	16	19	24	28	32	38
DGC1	4	5	5	6	6	6	5	–4
DGC2	7	9	12	14	17	19	22	25
DGC3	11	14	19	22	28	31	36	44
SSA1	12	14	16	17	19	20	22	24
SSB1	9	11	13	14	16	17	18	19
SSB2	12	16	20	23	28	31	35	41
SSB3	8	10	11	12	13	13	14	14
SSC1	4	6	7	8	9	9	9	9
SSC2	6	9	12	15	19	21	24	29
SSE1	8	10	11	13	14	14	15	15
SSE2	10	14	19	22	27	30	34	40
SSE3	10	11	12	13	15	15	16	16

NEW YORK, NEW YORK SSF (%) — 4851 DD65 (2697)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	10	14	19	22	27	30	35	41
WWB4	13	21	29	35	44	50	57	67
WWC2	13	20	28	34	42	48	55	64
TWA1	13	15	17	18	21	22	24	27
TWA2	11	14	17	20	23	26	30	35
TWA3	10	14	17	20	25	28	32	38
TWA4	9	13	17	20	25	28	33	39
TWB3	9	13	16	19	23	26	30	36
TWD4	13	19	26	31	39	44	51	60
TWE2	14	20	26	32	39	44	51	60
TWF3	7	11	14	17	21	24	28	34
TWJ2	11	17	24	29	36	42	48	57
DGA1	6	8	10	11	12	13	14	14
DGA2	9	12	16	18	23	25	29	34
DGA3	12	17	22	27	33	38	44	52
DGB1	6	8	10	11	13	14	16	17
DGB2	9	12	16	19	23	27	31	37
DGB3	13	17	23	28	35	40	47	56
DGC1	8	11	13	15	18	20	23	26
DGC2	11	15	20	23	29	33	38	45
DGC3	15	20	26	31	39	45	53	63
SSA1	16	19	23	26	30	33	37	43
SSB1	13	16	19	22	26	28	32	37
SSB2	17	22	28	33	39	44	50	58
SSB3	12	14	17	20	23	25	28	32
SSC1	9	12	15	18	22	25	29	34
SSC2	11	16	22	27	33	37	43	52
SSE1	13	17	21	24	28	31	35	41
SSE2	17	23	30	35	43	48	54	62
SSE3	13	16	19	22	25	27	31	35

CHARLOTTE, NORTH CAROLINA SSF (%) — 3226 DD65 (1794)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	13	23	31	39	45	54	59	66
WWB4	13	29	40	51	59	69	75	82
WWC2	13	29	39	50	58	67	74	81
TWA1	15	20	24	29	33	38	42	47
TWA2	13	21	27	33	38	45	50	57
TWA3	12	21	27	35	40	48	54	60
TWA4	11	20	27	35	41	49	54	61
TWB3	11	19	25	32	37	45	50	57
TWD4	13	26	36	46	53	63	69	76
TWE2	14	27	37	47	54	63	69	77
TWF3	9	18	24	31	36	44	50	56
TWJ2	11	24	34	44	51	61	67	74
DGA1	9	16	21	26	30	35	39	42
DGA2	10	18	24	31	37	44	49	55
DGA3	12	22	30	39	46	55	61	68
DGB1	9	16	21	28	32	39	44	49
DGB2	10	19	25	33	39	48	54	61
DGB3	12	23	31	40	48	58	65	73
DGC1	11	20	26	33	39	47	53	59
DGC2	12	22	29	38	45	55	61	69
DGC3	14	26	35	45	53	65	72	80
SSA1	17	26	33	40	45	53	58	64
SSB1	14	22	28	35	40	47	52	58
SSB2	17	29	37	46	52	61	67	74
SSB3	14	21	26	33	37	44	49	55
SSC1	11	20	27	34	40	48	53	60
SSC2	12	25	33	42	49	58	64	72
SSE1	16	26	34	42	47	55	61	68
SSE2	18	32	42	52	59	69	74	81
SSE3	15	23	29	35	40	47	51	57

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

RALEIGH-DURHAM, N. CAROLINA SSF (%)					3520 DD65 (1957)			
Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	11	21	28	36	41	50	55	62
WWB4	11	26	37	48	55	66	72	79
WWC2	12	26	36	46	54	64	70	77
TWA1	14	19	22	27	30	35	39	44
TWA2	12	19	24	30	35	42	47	53
TWA3	11	19	25	32	37	45	50	56
TWA4	9	18	24	32	37	45	51	57
TWB3	10	17	23	29	34	41	46	53
TWD4	11	24	33	43	50	60	66	73
TWE2	12	25	34	43	50	60	66	73
TWF3	8	16	21	28	33	41	46	52
TWJ2	10	22	31	40	47	57	63	71
DGA1	8	14	19	23	27	32	35	38
DGA2	9	16	22	29	34	41	45	51
DGA3	11	20	27	36	43	52	58	65
DGB1	8	14	19	24	29	35	39	44
DGB2	9	17	23	30	35	44	49	56
DGB3	11	21	28	37	44	55	61	70
DGC1	9	17	23	30	35	42	48	54
DGC2	10	20	27	35	41	50	57	64
DGC3	13	24	32	42	50	61	68	77
SSA1	16	24	30	37	42	50	54	61
SSB1	13	21	26	32	37	44	48	54
SSB2	15	26	34	43	49	58	63	70
SSB3	12	19	24	30	34	41	45	51
SSC1	10	18	24	31	36	44	49	56
SSC2	11	22	30	39	46	55	61	68
SSE1	14	24	31	38	44	52	57	63
SSE2	16	30	39	49	56	65	71	77
SSE3	14	21	26	32	37	43	48	54

BISMARCK, NORTH DAKOTA SSF (%)					9057 DD65 (5036)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	8	11	15	17	21	23	26	30
WWB4	11	17	24	30	37	43	49	58
WWC2	11	17	23	28	36	40	47	55
TWA1	12	13	15	16	17	18	19	21
TWA2	10	12	15	16	19	21	23	26
TWA3	9	11	14	16	20	22	25	29
TWA4	7	10	14	16	20	22	26	30
TWB3	8	10	13	16	19	21	24	29
TWD4	11	16	22	27	33	38	44	52
TWE2	11	16	22	27	33	37	43	51
TWF3	6	8	11	13	17	19	21	25
TWJ2	9	14	20	24	31	35	41	49
DGA1	5	6	7	8	8	8	8	7
DGA2	8	10	13	15	19	21	24	27
DGA3	11	15	20	23	29	33	38	45
DGB1	4	6	7	8	9	9	9	9
DGB2	8	10	14	16	20	22	25	29
DGB3	11	15	21	25	30	35	40	48
DGC1	6	8	10	12	14	15	16	17
DGC2	10	13	17	20	24	27	31	37
DGC3	13	18	24	28	35	39	46	55
SSA1	13	16	19	21	24	26	28	31
SSB1	11	13	15	17	20	22	24	27
SSB2	14	18	23	27	33	36	41	48
SSB3	10	11	13	15	17	18	20	21
SSC1	7	9	12	14	17	18	21	24
SSC2	9	13	18	22	27	31	35	42
SSE1	10	13	16	18	20	22	24	26
SSE2	13	18	24	28	34	38	43	50
SSE3	11	13	15	17	19	20	22	24

FARGO, NORTH DAKOTA SSF (%)						9278 DD65 (5159)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	6	8	11	12	15	16	18	20
WWB4	8	13	20	24	31	36	42	50
WWC2	8	13	19	23	29	33	39	46
TWA1	11	12	13	13	14	14	15	15
TWA2	9	10	12	13	15	16	17	18
TWA3	7	9	11	13	15	16	18	20
TWA4	6	8	10	12	15	16	19	21
TWB3	7	8	11	12	15	16	18	21
TWD4	8	13	18	22	28	32	37	44
TWE2	9	13	18	22	27	31	36	43
TWF3	4	6	8	10	12	13	15	17
TWJ2	7	11	16	20	25	29	34	41
DGA1	3	4	4	4	4	3	2	0
DGA2	6	8	11	12	15	16	18	20
DGA3	10	13	17	20	25	28	33	39
DGB1	3	4	4	4	4	4	3	1
DGB2	6	8	11	13	15	17	19	22
DGB3	10	13	18	21	26	30	35	41
DGC1	5	6	7	8	9	9	9	8
DGC2	8	11	14	16	20	22	25	29
DGC3	11	15	20	24	30	34	39	47
SSA1	12	14	16	17	19	21	22	24
SSB1	9	11	13	14	16	17	18	20
SSB2	12	16	20	23	28	31	36	41
SSB3	8	10	11	12	13	14	14	14
SSC1	5	7	8	10	11	12	13	14
SSC2	7	10	14	17	21	24	28	33
SSE1	8	10	12	13	14	15	16	15
SSE2	11	15	20	23	28	31	35	41
SSE3	10	11	13	14	15	16	16	17

CINCINNATI, OHIO SSF (%)					5079 DD65 (2824)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	10	13	17	21	25	28	32	38
WWB4	13	20	27	33	42	47	55	64
WWC2	13	19	27	32	40	45	52	62
TWA1	13	14	16	18	20	21	23	25
TWA2	11	14	17	19	22	25	28	32
TWA3	10	13	16	19	23	26	30	35
TWA4	9	12	16	19	23	26	31	36
TWB3	9	12	15	18	22	25	29	34
TWD4	12	18	25	30	37	42	49	58
TWE2	13	19	25	30	37	42	48	57
TWF3	7	10	13	16	20	23	26	31
TWJ2	11	16	23	28	35	40	46	55
DGA1	6	7	9	10	11	12	12	12
DGA2	9	12	15	18	21	24	27	32
DGA3	12	16	22	26	32	36	42	50
DGB1	6	7	9	10	12	13	14	14
DGB2	9	12	15	18	22	25	29	34
DGB3	12	17	23	27	33	38	44	53
DGC1	8	10	13	15	17	18	20	23
DGC2	11	15	19	22	27	31	36	42
DGC3	14	20	26	31	38	43	50	60
SSA1	15	19	23	25	29	32	36	41
SSB1	13	16	19	21	25	27	31	35
SSB2	16	22	27	32	38	42	48	56
SSB3	12	14	17	19	22	24	27	30
SSC1	8	11	15	17	21	23	26	31
SSC2	11	16	21	25	31	35	41	49
SSE1	13	16	20	23	27	30	33	38
SSE2	16	22	29	34	41	46	52	60
SSE3	13	16	19	21	24	26	29	33

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

CLEVELAND, OHIO SSF (%)						6160 DD65 (3425)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	6	9	11	13	15	16	18	20
WWB4	8	13	20	24	31	36	42	50
WWC2	8	13	19	23	29	34	39	47
TWA1	11	12	13	14	14	15	15	15
TWA2	9	10	12	13	15	16	17	19
TWA3	7	9	11	13	15	16	18	20
TWA4	6	8	10	12	15	17	19	22
TWB3	7	9	11	13	15	16	19	21
TWD4	9	13	18	22	28	32	37	45
TWE2	9	14	18	22	28	31	36	43
TWF3	5	6	8	10	12	13	15	17
TWJ2	7	11	16	20	25	29	34	41
DGA1	3	4	4	4	4	4	2	0
DGA2	7	8	11	12	15	16	18	21
DGA3	10	13	17	20	25	28	33	39
DGB1	3	4	4	5	4	4	3	1
DGB2	7	9	11	13	15	17	19	22
DGB3	10	14	18	21	26	30	35	42
DGC1	5	6	7	8	9	9	9	8
DGC2	8	11	14	16	20	22	25	29
DGC3	12	16	21	24	30	34	39	47
SSA1	13	15	18	19	22	24	26	28
SSB1	10	12	14	16	18	19	21	23
SSB2	13	17	22	25	30	34	38	44
SSB3	9	11	13	14	15	16	17	18
SSC1	5	7	9	10	11	12	13	14
SSC2	7	11	14	17	21	24	28	33
SSE1	9	12	14	15	17	18	19	20
SSE2	12	17	22	25	31	34	39	45
SSE3	11	13	14	16	17	18	19	20

COLUMBUS, OHIO SSF (%)						5705 DD65 (3172)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	8	11	14	16	20	22	25	29
WWB4	10	16	23	29	36	41	48	57
WWC2	10	16	22	27	34	39	46	54
TWA1	12	13	14	15	17	17	18	20
TWA2	10	12	14	16	18	20	22	25
TWA3	8	11	13	16	19	21	24	27
TWA4	7	10	13	15	19	21	24	29
TWB3	8	10	13	15	18	20	23	27
TWD4	10	15	21	26	32	37	43	51
TWE2	11	16	21	26	32	36	42	50
TWF3	6	8	11	13	16	18	20	24
TWJ2	9	13	19	23	30	34	40	48
DGA1	4	5	6	7	7	7	7	5
DGA2	7	10	12	15	18	20	22	26
DGA3	11	14	19	23	28	32	37	44
DGB1	4	5	6	7	8	8	8	7
DGB2	7	10	13	15	18	21	24	28
DGB3	11	15	20	24	29	33	39	47
DGC1	6	8	10	11	12	13	14	15
DGC2	9	12	16	19	23	26	30	35
DGC3	13	17	23	27	33	38	44	53
SSA1	14	17	20	22	25	27	30	34
SSB1	11	13	16	18	21	23	25	29
SSB2	15	19	24	28	34	38	43	50
SSB3	10	12	14	16	18	20	22	24
SSC1	7	9	11	13	16	17	19	22
SSC2	9	13	17	21	26	30	34	41
SSE1	11	14	17	19	22	24	26	29
SSE2	14	19	25	29	36	40	45	53
SSE3	12	14	16	18	20	22	24	26

OKLAHOMA CITY, OKLAHOMA SSF (%)						3699 DD65 (2057)		
Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	12	22	29	37	44	52	58	65
WWB4	12	28	38	50	58	68	74	81
WWC2	13	27	38	49	56	66	73	80
TWA1	14	20	23	28	32	37	41	46
TWA2	13	20	26	32	37	44	49	55
TWA3	12	20	26	33	39	47	52	59
TWA4	10	19	26	33	39	47	53	60
TWB3	10	18	24	31	36	44	49	56
TWD4	12	25	34	45	52	62	68	76
TWE2	13	26	35	45	53	62	68	76
TWF3	9	17	23	30	35	43	48	55
TWJ2	11	23	32	42	49	59	66	73
DGA1	8	15	20	25	29	34	37	41
DGA2	9	17	23	30	35	43	47	53
DGA3	11	21	29	38	45	54	60	67
DGB1	8	15	20	26	31	37	42	47
DGB2	10	18	24	31	37	46	52	59
DGB3	12	22	29	39	46	57	64	72
DGC1	10	18	24	32	37	46	51	58
DGC2	11	21	28	36	43	53	60	68
DGC3	13	25	33	44	52	64	71	79
SSA1	16	25	32	39	44	51	57	63
SSB1	14	21	27	33	38	45	50	56
SSB2	16	27	35	44	51	60	65	72
SSB3	13	20	25	31	36	42	47	53
SSC1	11	19	26	33	38	46	52	59
SSC2	12	23	32	41	48	57	63	71
SSE1	15	25	32	40	46	54	59	66
SSE2	17	31	40	51	58	67	73	80
SSE3	15	22	27	34	38	45	50	56

MEDFORD, OREGON SSF (%)						4935 DD65 (2744)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	16	21	26	31	36	40	45	51
WWB4	20	28	37	43	52	58	64	72
WWC2	20	28	36	42	50	56	62	70
TWA1	17	19	22	24	28	30	33	37
TWA2	16	20	24	27	32	35	39	44
TWA3	15	19	24	28	33	37	41	47
TWA4	14	19	24	28	34	37	42	49
TWB3	14	18	23	26	31	35	40	46
TWD4	19	26	34	39	47	52	59	67
TWE2	20	26	34	40	47	52	59	66
TWF3	12	16	21	25	30	33	38	44
TWJ2	17	24	31	37	45	50	56	64
DGA1	11	14	17	19	21	23	24	25
DGA2	13	17	22	26	31	34	38	43
DGA3	17	23	29	34	41	46	52	59
DGB1	11	14	18	20	23	25	28	30
DGB2	14	18	23	27	33	37	41	47
DGB3	17	23	30	36	44	49	55	63
DGC1	13	17	22	25	30	32	36	39
DGC2	16	21	27	32	39	43	48	55
DGC3	20	26	34	40	49	54	61	69
SSA1	21	26	30	34	39	42	46	51
SSB1	18	22	26	29	34	37	41	46
SSB2	22	28	35	40	47	51	57	64
SSB3	17	20	24	27	31	34	37	42
SSC1	14	18	23	27	32	35	39	44
SSC2	17	23	30	35	42	46	52	59
SSE1	19	24	29	33	38	41	45	50
SSE2	24	31	38	44	51	55	61	68
SSE3	18	22	26	29	33	36	40	44

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

SALEM, OREGON SSF (%)					4854 DD65 (2699)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	15	20	25	29	35	38	43	48
WWB4	19	27	36	42	50	56	63	71
WWC2	19	27	35	41	49	54	60	68
TWA1	16	19	22	24	27	29	31	35
TWA2	16	19	23	26	30	33	37	42
TWA3	15	19	23	27	32	35	40	45
TWA4	14	18	23	27	32	36	40	47
TWB3	14	18	22	25	30	34	38	44
TWD4	18	25	32	38	46	51	57	65
TWE2	19	26	33	38	46	51	57	65
TWF3	12	16	20	24	28	32	36	42
TWJ2	16	23	30	36	43	48	55	63
DGA1	10	13	16	18	20	21	23	23
DGA2	13	17	22	25	30	33	37	41
DGA3	17	22	28	33	40	45	51	58
DGB1	11	13	17	19	22	24	26	28
DGB2	13	18	22	26	32	35	40	45
DGB3	17	23	29	35	42	47	54	62
DGC1	13	16	21	24	28	30	33	37
DGC2	16	21	26	31	37	41	46	53
DGC3	19	26	33	39	47	53	59	68
SSA1	21	25	29	33	37	40	44	49
SSB1	17	21	25	28	33	36	39	44
SSB2	22	28	34	39	46	50	55	62
SSB3	16	20	23	26	30	33	36	40
SSC1	14	18	22	25	30	33	37	42
SSC2	17	22	29	33	40	45	50	57
SSE1	19	23	28	32	36	39	43	47
SSE2	23	30	37	42	49	54	59	66
SSE3	18	22	25	28	32	35	38	42

PHILADELPHIA, PENNSYLVANIA SSF (%)					4875 DD65 (2711)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	12	17	22	26	32	36	41	49
WWB4	16	24	33	40	49	55	63	72
WWC2	16	23	32	38	47	53	61	70
TWA1	14	16	19	21	24	26	29	33
TWA2	13	16	20	23	27	31	35	41
TWA3	12	16	20	24	29	33	38	44
TWA4	11	15	20	24	29	33	39	46
TWB3	11	15	19	22	27	31	36	42
TWD4	15	22	30	35	44	49	57	66
TWE2	16	22	30	36	44	49	56	66
TWF3	9	13	17	20	25	29	34	40
TWJ2	13	20	27	33	41	47	54	63
DGA1	8	10	12	14	17	18	19	20
DGA2	10	14	18	22	26	30	34	39
DGA3	14	19	25	30	37	42	49	58
DGB1	7	10	13	15	17	19	22	24
DGB2	11	14	19	22	28	31	37	43
DGB3	14	20	26	31	39	44	52	62
DGC1	10	13	17	19	23	26	30	34
DGC2	13	17	23	27	33	38	44	52
DGC3	16	22	29	35	44	50	58	69
SSA1	17	21	26	29	34	38	43	49
SSB1	14	18	22	25	29	33	37	43
SSB2	19	24	31	36	43	48	54	63
SSB3	13	16	20	22	26	29	33	38
SSC1	11	14	19	22	27	30	35	42
SSC2	14	19	26	31	38	43	49	58
SSE1	15	20	25	28	34	37	42	48
SSE2	19	26	34	40	48	53	60	68
SSE3	15	18	22	25	29	32	36	41

HARRISBURG, PENNSYLVANIA SSF (%)					5226 DD65 (2906)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	11	14	19	22	28	31	36	42
WWB4	14	21	29	36	45	51	58	68
WWC2	14	20	28	34	43	48	56	65
TWA1	13	15	17	19	21	23	25	28
TWA2	12	14	18	20	24	27	30	35
TWA3	10	14	18	21	25	28	33	39
TWA4	9	13	17	20	25	29	34	40
TWB3	10	13	16	19	24	27	31	37
TWD4	13	19	26	32	40	45	52	61
TWE2	14	20	27	32	40	45	52	61
TWF3	8	11	14	17	22	25	29	35
TWJ2	11	17	24	29	37	42	49	58
DGA1	6	8	10	11	13	14	15	15
DGA2	9	12	16	19	23	26	30	35
DGA3	12	17	23	27	34	38	45	53
DGB1	6	8	10	12	14	15	16	18
DGB2	9	12	16	19	24	27	32	38
DGB3	13	18	23	28	35	40	47	57
DGC1	8	11	14	16	19	21	24	27
DGC2	11	15	20	24	29	33	39	46
DGC3	15	20	27	32	40	46	53	64
SSA1	16	19	23	26	31	34	38	44
SSB1	13	16	19	22	26	29	32	38
SSB2	17	22	28	33	40	44	50	58
SSB3	12	14	17	20	23	25	28	33
SSC1	9	12	16	19	23	26	30	35
SSC2	12	17	22	27	34	38	44	52
SSE1	13	17	21	24	29	32	36	42
SSE2	17	23	30	36	43	48	55	63
SSE3	13	16	19	22	25	28	31	36

PITTSBURGH, PENNSYLVANIA SSF (%)					5937 DD65 (3301)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	7	9	12	14	17	19	21	24
WWB4	9	15	21	26	33	38	45	53
WWC2	9	14	20	25	32	36	42	50
TWA1	12	12	13	14	15	16	16	17
TWA2	9	11	13	14	16	18	19	22
TWA3	8	10	12	14	17	18	21	23
TWA4	6	9	11	14	17	19	21	25
TWB3	7	9	12	14	16	18	21	24
TWD4	9	14	20	24	30	34	40	48
TWE2	10	14	20	24	30	34	39	46
TWF3	5	7	9	11	14	15	17	20
TWJ2	8	12	17	21	27	31	37	44
DGA1	4	5	5	5	5	5	4	2
DGA2	7	9	11	13	16	18	20	23
DGA3	10	14	18	21	26	30	35	41
DGB1	4	4	5	6	6	6	5	3
DGB2	7	9	12	14	17	19	21	25
DGB3	10	14	19	22	28	32	37	44
DGC1	5	7	8	9	10	11	11	11
DGC2	9	11	15	17	21	24	27	32
DGC3	12	16	21	26	32	36	42	50
SSA1	13	16	19	21	23	25	28	31
SSB1	11	13	15	17	19	21	23	26
SSB2	14	18	23	27	32	36	40	47
SSB3	10	11	13	15	17	18	19	21
SSC1	6	8	10	11	13	15	16	18
SSC2	8	12	16	19	23	27	31	37
SSE1	10	12	15	17	19	21	23	24
SSE2	13	18	23	27	33	37	42	48
SSE3	11	13	15	17	19	20	21	23

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

PROVIDENCE, RHODE ISLAND SSF (%)					5974 DD65 (3322)			
Type	**LCR = 100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**	**15 (85)**
WWA3	10	13	18	21	26	29	33	40
WWB4	13	20	28	34	43	49	56	66
WWC2	13	19	27	33	41	47	54	63
TWA1	13	14	16	18	20	21	23	26
TWA2	11	14	17	19	22	25	28	33
TWA3	10	13	16	19	24	27	31	36
TWA4	9	12	16	19	24	27	31	38
TWB3	9	12	15	18	22	25	29	35
TWD4	12	18	25	30	38	43	50	59
TWE2	13	19	25	30	38	43	50	59
TWF3	7	10	13	16	20	23	27	32
TWJ2	11	16	23	28	35	40	47	56
DGA1	6	7	9	10	11	12	13	13
DGA2	8	11	15	18	22	24	28	33
DGA3	12	16	21	26	32	37	43	51
DGB1	5	7	9	10	12	13	14	15
DGB2	9	12	15	18	22	26	30	36
DGB3	12	17	22	27	34	39	45	55
DGC1	7	10	12	14	17	19	21	25
DGC2	10	14	19	22	28	31	37	44
DGC3	14	19	26	31	38	44	52	62
SSA1	15	19	22	25	30	33	36	42
SSB1	12	15	19	21	25	28	31	36
SSB2	16	21	27	32	38	43	49	57
SSB3	11	14	17	19	22	24	27	31
SSC1	8	11	15	17	21	24	27	32
SSC2	11	16	21	25	32	36	42	50
SSE1	13	16	20	23	27	30	34	39
SSE2	16	22	29	34	42	47	53	61
SSE3	13	16	19	21	24	27	30	34

RAPID CITY, SOUTH DAKOTA SSF (%)					7332 DD65 (4077)			
Type	**LCR = 100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**	**15 (85)**
WWA3	13	18	23	27	33	37	42	50
WWB4	17	25	34	40	50	56	63	73
WWC2	17	24	33	39	48	54	61	70
TWA1	15	17	19	21	24	27	30	34
TWA2	13	17	21	24	28	32	36	42
TWA3	13	17	21	25	30	34	38	45
TWA4	11	16	21	25	30	34	39	47
TWB3	11	15	20	23	28	32	37	43
TWD4	16	23	30	36	45	50	57	66
TWE2	17	23	31	37	45	50	57	66
TWF3	10	13	18	21	26	30	35	41
TWJ2	14	21	28	34	42	47	54	64
DGA1	8	11	13	15	18	19	20	21
DGA2	11	15	19	22	27	31	35	40
DGA3	14	20	26	31	38	43	50	58
DGB1	8	11	14	16	19	21	23	26
DGB2	11	15	20	32	29	33	38	44
DGB3	15	20	27	32	40	45	53	62
DGC1	10	14	18	21	25	27	31	35
DGC2	13	18	24	28	34	39	45	53
DGC3	17	23	31	36	45	51	59	69
SSA1	18	22	26	30	34	38	42	48
SSB1	15	19	22	25	30	33	37	42
SSB2	19	25	31	36	43	48	54	62
SSB3	13	16	20	23	26	29	33	37
SSC1	11	15	20	23	28	31	36	42
SSC2	14	20	27	32	39	44	50	59
SSE1	16	20	25	28	33	37	41	47
SSE2	20	27	34	40	47	52	59	67
SSE3	15	18	22	25	29	32	35	40

CHARLESTON, SOUTH CAROLINA SSF (%)					2150 DD65 (1195)			
Type	**LCR = 200 (1135)**	**100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**
WWA3	18	31	40	50	57	66	72	79
WWB4	19	38	50	62	70	79	85	90
WWC2	20	38	49	61	69	78	84	89
TWA1	17	25	30	37	41	48	53	59
TWA2	17	27	34	42	48	57	62	69
TWA3	16	28	36	45	51	60	66	73
TWA4	15	27	36	45	52	61	67	74
TWB3	14	25	33	41	47	56	62	69
TWD4	18	35	45	56	64	74	79	86
TWE2	19	36	46	57	65	74	80	86
TWF3	13	24	32	41	47	56	62	69
TWJ2	17	32	43	54	62	72	77	84
DGA1	13	23	29	36	41	48	51	56
DGA2	13	24	32	41	47	55	60	67
DGA3	16	29	38	49	57	66	72	78
DGB1	13	23	31	39	45	54	59	65
DGB2	14	25	34	43	51	61	67	74
DGB3	16	29	39	51	60	71	77	83
DGC1	15	27	36	46	53	63	69	75
DGC2	16	29	38	49	58	68	75	81
DGC3	18	33	44	57	66	77	83	89
SSA1	22	33	41	50	56	65	70	76
SSB1	18	29	36	44	50	58	64	70
SSB2	22	36	46	56	63	72	77	83
SSB3	17	27	34	42	48	56	61	68
SSC1	16	28	36	45	51	60	66	73
SSC2	18	32	42	53	60	70	76	82
SSE1	21	34	43	53	60	69	74	80
SSE2	24	42	53	64	71	80	85	90
SSE3	19	29	36	44	50	58	64	70

MEMPHIS, TENNESSEE SSF (%)					3237 DD65 (1800)			
Type	**LCR = 200 (1135)**	**100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**
WWA3	11	21	27	35	41	49	54	61
WWB4	11	26	36	47	54	65	71	78
WWC2	12	26	35	46	53	63	69	77
TWA1	14	19	22	27	30	35	38	43
TWA2	12	19	24	30	35	41	46	52
TWA3	11	19	25	31	36	44	49	55
TWA4	9	18	24	31	37	44	50	56
TWB3	10	17	23	29	34	41	46	52
TWD4	11	24	32	42	49	59	65	72
TWE2	12	25	33	43	50	59	65	72
TWF3	8	16	21	28	33	40	45	51
TWJ2	10	22	30	40	47	56	62	70
DGA1	8	14	18	23	26	31	34	37
DGA2	9	16	22	28	33	40	44	50
DGA3	11	20	27	36	42	51	57	64
DGB1	8	14	19	24	28	34	38	43
DGB2	9	17	22	29	35	43	48	55
DGB3	11	21	28	37	43	54	60	69
DGC1	10	17	23	29	34	41	46	52
DGC2	11	20	26	34	40	49	56	63
DGC3	13	24	31	41	49	60	67	76
SSA1	16	24	30	37	42	49	54	60
SSB1	13	21	26	32	36	43	47	53
SSB2	15	26	34	42	49	57	63	70
SSB3	12	19	24	30	34	40	44	50
SSC1	10	18	24	31	36	43	48	54
SSC2	11	22	30	38	45	54	59	67
SSE1	14	24	30	38	43	51	56	62
SSE2	16	29	38	48	55	64	70	77
SSE3	14	21	26	32	36	43	47	53

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

KNOXVILLE, TENNESSEE SSF (%) 3486 DD65 (1938)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	10	18	24	31	36	44	49	55
WWB4	9	23	32	43	50	60	66	74
WWC2	10	23	32	42	49	58	65	72
TWA1	13	17	21	24	27	32	35	39
TWA2	11	17	22	27	31	37	41	47
TWA3	10	17	22	28	33	39	44	50
TWA4	8	16	21	28	33	40	45	51
TWB3	9	15	20	26	30	37	41	47
TWD4	10	21	29	38	45	54	60	68
TWE2	11	22	30	39	46	55	60	68
TWF3	7	14	19	25	29	36	40	46
TWJ2	8	19	27	36	43	52	58	65
DGA1	7	12	16	20	23	27	29	32
DGA2	8	15	19	25	30	36	40	45
DGA3	10	18	25	32	38	47	53	60
DGB1	7	12	16	21	24	29	32	36
DGB2	8	15	20	26	31	38	43	49
DGB3	10	19	26	33	40	49	55	64
DGC1	8	15	20	25	29	36	40	45
DGC2	9	18	24	31	36	44	50	57
DGC3	12	22	29	38	45	55	62	71
SSA1	15	22	28	34	38	45	49	55
SSB1	12	19	24	29	33	39	43	49
SSB2	14	24	31	39	45	53	59	65
SSB3	12	18	22	27	31	36	40	45
SSC1	9	16	21	27	32	38	43	49
SSC2	9	19	27	35	41	49	55	62
SSE1	13	21	27	34	39	48	51	57
SSE2	14	27	35	44	51	60	65	72
SSE3	13	19	24	29	33	39	43	48

NASHVILLE, TENNESSEE SSF (%) 3704 DD65 (2059)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	8	15	20	26	31	37	42	47
WWB4	7	19	28	37	44	54	60	68
WWC2	8	19	27	36	43	52	58	66
TWA1	12	16	18	21	24	27	30	33
TWA2	10	15	19	23	27	32	35	40
TWA3	8	14	19	24	28	34	38	43
TWA4	7	13	18	24	28	34	38	44
TWB3	7	13	17	22	26	32	35	41
TWD4	8	18	25	34	40	48	54	61
TWE2	9	19	26	34	40	48	54	61
TWF3	6	11	16	21	24	30	34	39
TWJ2	6	16	23	31	37	46	51	59
DGA1	6	10	13	16	18	21	23	25
DGA2	7	12	17	21	25	31	34	39
DGA3	9	16	22	28	34	41	47	54
DGB1	6	10	13	16	19	22	25	28
DGB2	7	13	17	22	26	32	36	42
DGB3	9	17	22	29	35	43	49	57
DGC1	7	12	16	20	24	29	32	36
DGC2	8	15	20	26	31	38	43	49
DGC3	10	19	25	33	39	49	55	64
SSA1	13	20	25	30	34	39	43	49
SSB1	11	17	21	25	29	34	38	42
SSB2	12	21	28	35	40	48	53	60
SSB3	10	15	19	23	27	31	35	39
SSC1	7	13	18	23	26	32	36	41
SSC2	8	16	23	30	35	43	48	55
SSE1	11	18	23	29	33	39	44	49
SSE2	12	23	31	39	45	53	59	66
SSE3	12	17	21	25	29	34	37	41

AUSTIN, TEXAS SSF (%) 1737 DD65 (966)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	21	37	47	58	65	75	80	86
WWB4	24	45	58	70	77	86	90	94
WWC2	24	44	57	69	76	85	89	94
TWA1	20	29	35	42	48	56	61	67
TWA2	20	32	40	49	56	65	70	77
TWA3	19	33	42	52	59	68	74	81
TWA4	18	32	42	52	60	69	75	82
TWB3	17	30	38	48	55	64	70	77
TWD4	22	41	52	64	72	81	86	91
TWE2	24	42	53	65	73	81	86	91
TWF3	16	29	38	48	55	64	70	77
TWJ2	21	39	50	62	70	79	84	90
DGA1	16	28	36	44	49	57	61	66
DGA2	16	29	38	48	55	64	69	75
DGA3	19	34	45	57	65	74	79	84
DGB1	16	29	38	48	56	64	69	75
DGB2	17	30	41	52	60	70	76	82
DGB3	19	35	46	60	68	79	84	89
DGC1	19	33	44	56	64	74	79	84
DGC2	19	34	46	59	68	77	83	88
DGC3	22	39	52	66	75	85	89	93
SSA1	25	39	48	58	65	73	78	84
SSB1	21	34	42	51	58	67	72	79
SSB2	26	42	53	63	71	79	84	89
SSB3	20	32	40	49	56	65	70	77
SSC1	19	33	42	53	60	69	75	81
SSC2	22	39	50	61	68	78	83	89
SSE1	25	41	51	62	69	77	82	88
SSE2	29	49	61	72	79	87	91	94
SSE3	22	34	43	52	58	67	72	79

BROWNSVILLE, TEXAS SSF (%) 650 DD65 (361)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	39	60	72	82	88	94	96	98
WWB4	45	70	82	90	94	98	99	100
WWC2	45	69	81	90	94	97	99	99
TWA1	30	45	54	64	71	79	84	89
TWA2	33	51	63	73	80	87	91	95
TWA3	34	54	66	76	83	90	93	96
TWA4	34	54	66	77	84	90	94	97
TWB3	31	50	61	72	79	87	91	95
TWD4	41	64	76	86	91	96	98	99
TWE2	42	65	77	87	92	96	98	99
TWF3	30	50	62	73	80	88	91	95
TWJ2	39	62	75	85	90	95	97	99
DGA1	31	50	61	70	76	83	87	90
DGA2	31	51	63	73	80	87	90	94
DGA3	34	57	70	80	86	91	93	95
DGB1	32	54	67	78	84	89	92	94
DGB2	32	55	69	80	86	92	95	97
DGB3	34	60	74	85	90	94	96	97
DGC1	36	62	76	85	90	94	95	97
DGC2	35	61	75	86	91	95	97	99
DGC3	39	66	80	90	94	97	98	98
SSA1	42	62	73	82	87	93	96	98
SSB1	36	55	66	76	83	89	93	96
SSB2	44	65	77	86	91	95	97	99
SSB3	35	54	65	75	81	88	92	95
SSC1	35	55	67	78	84	91	94	97
SSC2	39	62	74	84	90	95	97	99
SSE1	45	66	77	86	91	95	97	99
SSE2	51	74	85	92	96	98	99	100
SSE3	37	56	67	77	83	90	93	96

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

DALLAS, TEXAS SSF (%) — 2297 DD65 (1277)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	17	30	39	49	56	66	72	79
WWB4	19	37	49	62	70	79	85	90
WWC2	19	37	49	61	69	78	84	89
TWA1	17	24	30	36	41	48	52	59
TWA2	16	26	33	42	48	56	62	69
TWA3	16	27	35	44	50	60	65	73
TWA4	14	26	35	44	51	60	66	74
TWB3	14	24	32	40	47	56	62	69
TWD4	18	34	45	56	64	74	79	86
TWE2	19	35	46	57	65	74	80	86
TWF3	13	23	31	40	46	56	62	69
TWJ2	16	32	42	54	61	71	77	84
DGA1	12	22	29	36	41	47	51	56
DGA2	13	24	31	40	47	55	60	66
DGA3	15	28	38	49	56	66	72	78
DGB1	12	22	30	38	45	54	59	64
DGB2	13	24	33	43	51	61	67	74
DGB3	16	28	38	50	59	71	77	83
DGC1	15	26	35	45	53	63	69	75
DGC2	15	28	38	49	57	68	74	81
DGC3	18	32	43	57	66	77	83	89
SSA1	21	32	40	49	56	64	70	76
SSB1	17	28	35	43	49	58	63	70
SSB2	21	35	45	55	62	71	77	83
SSB3	17	26	33	41	47	55	60	67
SSC1	15	27	35	44	51	60	66	73
SSC2	17	32	42	52	60	70	76	82
SSE1	20	33	42	52	59	68	74	80
SSE2	23	41	52	63	70	79	84	90
SSE3	18	28	35	43	49	58	63	70

HOUSTON, TEXAS SSF (%) — 1434 DD65 (797)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	21	37	47	58	65	74	80	86
WWB4	24	45	58	70	77	86	90	94
WWC2	24	44	57	69	76	85	89	93
TWA1	20	29	35	42	48	55	61	67
TWA2	20	32	40	49	56	65	70	77
TWA3	20	33	42	52	59	68	74	80
TWA4	18	32	42	52	59	69	75	81
TWB3	18	30	38	48	55	64	70	77
TWD4	22	41	52	64	72	81	86	91
TWE2	24	42	53	65	72	81	86	91
TWF3	16	29	38	48	55	64	70	77
TWJ2	21	38	50	62	69	79	84	89
DGA1	16	28	36	44	49	56	61	65
DGA2	16	29	38	48	55	63	69	74
DGA3	19	34	45	57	64	74	79	84
DGB1	16	28	38	48	55	64	69	74
DGB2	17	30	40	52	60	70	75	81
DGB3	19	35	46	59	68	78	83	89
DGC1	18	33	44	56	64	73	78	83
DGC2	19	34	46	59	67	77	82	88
DGC3	21	39	52	66	75	84	89	93
SSA1	25	39	48	58	65	73	78	84
SSB1	21	34	42	52	58	67	72	79
SSB2	26	42	53	64	71	79	84	89
SSB3	20	32	41	50	56	65	70	77
SSC1	19	33	42	52	60	69	75	81
SSC2	22	38	49	61	68	77	83	88
SSE1	25	41	51	62	69	77	82	88
SSE2	29	49	61	72	79	87	90	94
SSE3	22	34	43	52	59	67	73	79

EL PASO, TEXAS SSF (%) — 2685 DD65 (1493)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	22	38	49	60	68	77	83	88
WWB4	25	47	60	72	80	88	92	95
WWC2	25	46	59	71	79	87	91	95
TWA1	20	29	36	44	49	58	63	70
TWA2	20	33	41	51	58	67	73	80
TWA3	20	34	44	54	61	71	77	83
TWA4	19	34	44	54	62	72	77	84
TWB3	18	31	40	50	57	67	73	79
TWD4	23	42	54	66	74	83	88	93
TWE2	24	43	55	67	75	84	88	93
TWF3	16	30	40	50	57	67	73	80
TWJ2	21	40	52	64	72	81	86	91
DGA1	16	29	37	46	52	59	64	69
DGA2	17	30	40	50	57	66	71	77
DGA3	19	35	47	59	67	76	81	86
DGB1	16	30	40	51	58	67	72	78
DGB2	17	31	42	55	63	73	79	84
DGB3	19	36	48	62	71	81	86	91
DGC1	19	35	47	59	68	77	82	86
DGC2	20	36	48	62	70	80	85	90
DGC3	22	40	55	69	78	87	91	94
SSA1	25	39	49	58	65	74	79	85
SSB1	21	34	43	52	59	68	73	80
SSB2	26	42	53	64	71	80	85	90
SSB3	20	32	41	50	56	65	71	77
SSC1	20	34	44	55	62	72	77	84
SSC2	22	40	51	63	71	80	85	90
SSE1	25	41	52	62	69	78	83	89
SSE2	29	49	61	73	80	87	91	95
SSE3	22	35	43	52	59	68	73	80

LUBBOCK, TEXAS SSF (%) — 3551 DD65 (1974)

Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	17	30	40	50	57	67	73	80
WWB4	18	38	50	63	71	80	86	91
WWC2	19	37	49	61	69	79	85	90
TWA1	17	24	30	36	41	48	53	60
TWA2	16	26	34	42	48	57	63	70
TWA3	15	27	35	44	51	60	67	74
TWA4	14	26	35	45	52	61	67	75
TWB3	14	24	32	41	47	56	62	70
TWD4	17	34	45	57	65	75	80	87
TWE2	19	35	46	58	65	75	81	87
TWF3	12	23	31	40	47	56	63	70
TWJ2	16	32	43	54	62	72	78	85
DGA1	12	22	29	36	41	48	52	57
DGA2	13	23	32	41	47	56	61	67
DGA3	15	28	38	49	57	67	73	79
DGB1	12	22	30	39	46	55	60	66
DGB2	13	24	33	43	51	62	68	75
DGB3	15	28	39	51	60	72	78	84
DGC1	14	26	35	46	54	65	70	76
DGC2	15	28	38	50	59	70	76	82
DGC3	17	32	44	57	67	79	84	90
SSA1	21	33	41	50	56	65	70	77
SSB1	17	28	35	43	50	58	64	71
SSB2	21	35	45	55	63	72	77	84
SSB3	16	26	33	41	47	55	61	68
SSC1	15	27	35	45	52	61	67	74
SSC2	17	32	42	53	61	71	77	83
SSE1	20	34	43	53	60	69	74	81
SSE2	23	41	52	63	71	80	85	90
SSE3	18	28	36	44	50	58	64	70

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

SAN ANTONIO, TEXAS SSF (%)						1570 DD65 (873)		
Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	23	40	50	61	69	78	83	88
WWB4	26	48	61	73	80	88	92	95
WWC2	26	47	60	72	79	87	91	95
TWA1	21	30	37	45	50	59	64	71
TWA2	21	34	42	52	59	68	74	80
TWA3	21	35	45	55	62	71	77	83
TWA4	20	35	45	55	63	72	78	84
TWB3	19	32	41	51	58	67	73	80
TWD4	24	43	55	67	75	83	88	93
TWE2	26	44	56	68	75	84	88	93
TWF3	18	31	41	51	58	68	74	80
TWJ2	22	41	53	65	73	82	87	91
DGA1	17	30	38	47	53	60	64	69
DGA2	18	32	41	51	58	67	72	78
DGA3	20	36	48	60	68	77	81	86
DGB1	17	31	41	52	59	68	73	78
DGB2	18	33	44	56	64	74	79	85
DGB3	20	37	50	63	72	81	86	91
DGC1	20	36	48	60	68	77	82	86
DGC2	21	37	49	63	71	80	85	90
DGC3	23	42	56	70	78	87	91	94
SSA1	27	41	51	61	68	76	81	87
SSB1	23	36	45	54	61	70	75	82
SSB2	27	45	55	66	73	82	86	91
SSB3	22	34	43	52	59	68	73	80
SSC1	21	35	45	56	63	72	78	84
SSC2	23	41	53	64	71	80	85	91
SSE1	27	44	54	65	72	80	85	90
SSE2	31	52	64	75	82	89	92	96
SSE3	24	37	45	55	62	70	76	82

SALT LAKE CITY, UTAH SSF (%)						5988 DD65 (3329)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	19	25	32	37	44	49	55	64
WWB4	23	33	43	50	60	66	73	82
WWC2	23	32	42	49	59	65	72	80
TWA1	18	21	25	28	32	35	39	45
TWA2	18	22	28	32	38	42	47	54
TWA3	17	22	29	33	40	44	50	58
TWA4	16	22	28	33	40	45	51	60
TWB3	16	21	26	31	37	42	48	55
TWD4	22	30	39	45	55	60	68	76
TWE2	23	31	39	46	55	61	68	76
TWF3	14	19	25	30	36	41	46	54
TWJ2	20	28	37	43	52	58	65	74
DGA1	12	16	20	23	27	30	32	35
DGA2	15	20	26	30	36	41	46	52
DGA3	19	25	33	39	47	53	60	68
DGB1	13	17	21	25	30	33	37	41
DGB2	15	21	27	32	39	44	50	58
DGB3	19	26	34	40	50	56	64	73
DGC1	15	20	26	31	37	41	46	52
DGC2	18	24	31	37	45	51	58	66
DGC3	22	29	38	46	56	62	70	79
SSA1	23	28	34	38	44	48	54	60
SSB1	19	24	29	33	39	43	48	55
SSB2	24	31	39	45	52	58	64	72
SSB3	18	22	27	31	36	39	44	50
SSC1	16	22	28	32	39	43	49	57
SSC2	20	27	35	41	49	55	62	70
SSE1	22	27	34	38	45	49	55	62
SSE2	27	35	44	50	58	63	70	78
SSE3	20	24	29	33	38	42	47	53

BRYCE CANYON, UTAH SSF (%)						9136 DD65 (5080)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	16	22	30	35	43	59	56	65
WWB4	21	31	42	49	60	67	75	84
WWC2	21	30	40	48	58	65	73	82
TWA1	16	19	22	25	30	33	38	44
TWA2	15	20	25	29	36	40	46	55
TWA3	15	20	26	31	38	43	50	59
TWA4	14	19	26	31	39	44	51	60
TWB3	13	18	24	29	35	40	47	55
TWD4	19	28	37	44	54	60	68	78
TWE2	20	28	38	45	54	60	68	78
TWF3	12	17	23	27	34	39	46	55
TWJ2	17	25	35	42	51	58	65	75
DGA1	10	14	18	21	25	28	30	34
DGA2	12	17	23	28	35	39	44	51
DGA3	16	23	31	37	46	52	60	69
DGB1	10	14	18	22	27	31	36	41
DGB2	13	18	24	29	37	42	49	58
DGB3	17	23	32	38	48	55	64	74
DGC1	13	17	23	28	35	39	46	54
DGC2	15	21	29	35	43	50	58	67
DGC3	19	27	36	43	55	62	72	81
SSA1	23	29	35	40	47	52	58	66
SSB1	18	23	29	34	40	45	51	59
SSB2	24	32	40	46	55	61	68	76
SSB3	17	22	27	32	38	42	47	55
SSC1	14	19	25	30	37	42	49	58
SSC2	18	25	33	40	49	55	62	72
SSE1	21	28	35	41	48	53	60	68
SSE2	27	36	46	53	62	68	75	83
SSE3	19	24	30	34	40	45	50	58

BURLINGTON, VERMONT SSF (%)						7878 DD65 (4380)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	4	6	8	9	10	11	12	13
WWB4	6	10	16	20	26	31	36	44
WWC2	6	10	15	19	25	29	34	41
TWA1	10	11	11	11	11	11	11	10
TWA2	7	8	9	10	11	12	12	13
TWA3	6	7	8	10	11	12	13	14
TWA4	4	6	8	9	11	12	14	15
TWB3	5	7	8	10	11	12	14	16
TWD4	7	10	15	19	24	27	32	39
TWE2	7	11	15	18	23	26	31	37
TWF3	3	4	6	7	8	9	10	11
TWJ2	5	9	13	16	21	25	29	35
DGA1	2	2	2	1	1	0	–1	–5
DGA2	5	7	8	10	11	13	14	16
DGA3	8	11	15	17	22	25	29	34
DGB1	2	2	2	1	1	0	–1	–4
DGB2	5	7	9	10	12	13	15	17
DGB3	9	12	15	18	23	26	31	37
DGC1	3	4	4	4	5	4	3	2
DGC2	7	9	11	13	16	18	20	23
DGC3	10	13	18	21	26	30	35	42
SSA1	11	13	14	16	17	18	20	21
SSB1	9	10	11	13	14	15	16	17
SSB2	11	15	19	22	26	29	33	38
SSB3	8	9	10	10	11	11	12	11
SSC1	4	5	6	6	7	7	7	7
SSC2	5	8	11	14	17	19	22	27
SSE1	7	8	10	11	12	12	12	11
SSE2	9	13	17	21	25	28	32	37
SSE3	9	10	11	12	13	13	14	14

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

NORFOLK, VIRGINIA SSF (%)					3493 DD65 (1942)			
Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	12	22	29	37	42	51	56	63
WWB4	12	27	37	49	56	67	73	80
WWC2	12	27	37	47	55	65	71	78
TWA1	14	19	23	27	31	36	40	45
TWA2	12	20	25	31	36	43	48	54
TWA3	11	20	26	33	38	46	51	57
TWA4	10	19	25	33	38	46	52	59
TWB3	10	18	23	30	35	42	48	54
TWD4	12	25	34	44	51	61	67	74
TWE2	13	26	35	44	51	61	67	74
TWF3	8	16	22	29	34	42	47	53
TWJ2	10	23	32	41	48	58	64	72
DGA1	8	15	19	24	28	33	36	39
DGA2	9	17	23	29	35	42	46	52
DGA3	11	21	28	37	44	53	59	66
DGB1	8	15	20	25	30	36	40	45
DGB2	9	17	23	31	36	45	50	58
DGB3	11	21	29	38	45	56	63	71
DGC1	10	18	24	31	36	44	49	56
DGC2	11	20	27	36	42	52	58	66
DGC3	13	24	33	43	51	62	70	78
SSA1	16	25	31	38	43	50	55	62
SSB1	13	21	26	33	38	44	49	55
SSB2	16	27	35	44	50	59	64	71
SSB3	13	20	25	31	35	42	46	52
SSC1	10	19	25	32	37	45	50	57
SSC2	11	23	31	40	46	56	62	69
SSE1	15	25	31	39	45	53	58	64
SSE2	16	30	40	50	57	66	72	78
SSE3	14	22	27	33	38	44	49	55

ROANOKE, VIRGINIA SSF (%)						4314 DD65 (2399)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	17	23	30	35	42	47	54	63
WWB4	22	31	41	49	59	65	73	82
WWC2	21	30	40	47	57	64	71	80
TWA1	17	20	23	26	30	33	37	43
TWA2	16	21	26	30	36	40	45	53
TWA3	16	21	27	31	38	43	49	57
TWA4	15	20	26	31	38	43	50	59
TWB3	14	19	25	29	35	40	46	54
TWD4	20	28	37	44	53	59	67	76
TWE2	21	29	38	44	53	59	67	76
TWF3	13	17	23	28	34	39	45	53
TWJ2	18	26	35	41	50	57	64	74
DGA1	11	14	18	21	25	27	30	33
DGA2	13	18	24	28	35	39	44	50
DGA3	17	23	31	37	46	52	59	67
DGB1	11	15	19	22	27	30	35	40
DGB2	14	19	25	30	37	42	48	56
DGB3	18	24	32	38	48	54	63	73
DGC1	14	18	24	28	34	38	44	51
DGC2	16	22	29	35	43	49	56	65
DGC3	20	28	36	43	54	61	70	79
SSA1	21	27	32	37	43	48	54	61
SSB1	18	22	28	32	38	42	47	55
SSB2	23	30	38	44	52	57	64	73
SSB3	17	21	26	29	35	39	44	50
SSC1	15	20	26	30	37	41	47	56
SSC2	18	25	33	39	48	53	61	70
SSE1	20	26	33	37	44	49	55	63
SSE2	25	34	43	49	58	64	71	79
SSE3	18	23	28	32	37	41	46	53

RICHMOND, VIRGINIA SSF (%)					3941 DD65 (2191)			
Type	LCR = 200 (1135)	100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)
WWA3	9	17	23	30	35	43	48	54
WWB4	8	22	31	42	49	59	65	73
WWC2	9	22	31	41	48	57	64	71
TWA1	13	17	20	24	26	31	34	38
TWA2	11	17	21	26	30	36	40	46
TWA3	9	16	21	27	32	38	43	49
TWA4	8	15	21	27	32	39	44	50
TWB3	8	15	19	25	29	36	40	46
TWD4	9	20	28	37	44	53	59	67
TWE2	10	21	29	38	45	54	60	67
TWF3	6	13	18	24	28	35	39	45
TWJ2	8	19	26	35	42	51	57	64
DGA1	6	11	15	19	22	26	28	30
DGA2	7	14	19	24	29	35	39	44
DGA3	9	18	24	31	37	46	52	59
DGB1	6	11	15	20	23	28	31	35
DGB2	8	14	19	25	30	37	42	48
DGB3	10	18	25	33	39	48	55	63
DGC1	8	14	19	24	29	35	39	44
DGC2	9	17	23	30	35	43	49	56
DGC3	11	21	28	37	44	54	61	70
SSA1	14	21	27	33	37	43	48	53
SSB1	12	18	23	28	32	38	42	47
SSB2	13	23	30	38	44	52	57	64
SSB3	11	17	21	26	29	35	39	44
SSC1	8	15	20	26	31	37	42	48
SSC2	9	19	26	34	40	48	54	61
SSE1	12	20	26	33	37	44	49	55
SSE2	13	25	34	43	49	58	64	71
SSE3	13	19	23	28	32	37	41	46

SEATTLE-TACOMA, WASHINGTON SSF (%)						5188 DD65 (2885)		
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	14	18	23	26	30	33	36	41
WWB4	17	25	32	38	46	51	57	64
WWC2	17	24	32	37	44	49	55	62
TWA1	16	18	20	22	25	26	28	31
TWA2	14	18	21	24	27	30	33	36
TWA3	14	17	21	24	29	31	35	39
TWA4	12	17	21	24	29	32	35	40
TWB3	13	16	20	23	27	30	34	38
TWD4	17	23	30	35	42	46	52	59
TWE2	17	24	30	35	42	46	51	58
TWF3	11	14	18	21	25	28	31	36
TWJ2	15	21	28	33	39	44	49	57
DGA1	9	12	14	16	17	18	18	18
DGA2	12	16	20	23	27	30	33	37
DGA3	16	21	27	31	37	41	46	53
DGB1	10	12	15	17	19	20	21	22
DGB2	13	16	21	24	29	32	35	40
DGB3	16	22	28	33	39	44	49	57
DGC1	12	15	19	21	24	26	28	30
DGC2	15	19	25	28	34	37	42	47
DGC3	19	24	31	36	44	49	54	62
SSA1	19	23	27	30	34	36	39	43
SSB1	16	20	23	26	30	32	35	38
SSB2	21	26	32	36	42	46	51	57
SSB3	15	18	22	24	27	29	31	34
SSC1	12	16	20	22	26	28	31	35
SSC2	15	20	26	30	36	40	45	51
SSE1	17	21	25	28	32	34	38	39
SSE2	21	27	34	38	44	48	53	58
SSE3	17	20	23	26	29	31	33	36

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

SPOKANE, WASHINGTON SSF (%) — 6839 DD65 (3803)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	11	14	18	21	24	27	29	32
WWB4	14	20	28	33	40	45	51	58
WWC2	14	20	27	32	38	43	48	55
TWA1	14	15	17	19	21	22	23	25
TWA2	12	15	18	20	23	24	27	29
TWA3	11	14	17	20	23	25	28	31
TWA4	10	13	17	20	23	26	29	33
TWB3	10	13	17	19	22	25	28	32
TWD4	13	19	25	30	36	41	46	53
TWE2	14	20	26	30	36	40	45	52
TWF3	8	11	14	17	20	22	25	28
TWJ2	12	17	23	28	34	38	43	50
DGA1	7	9	10	11	12	12	12	11
DGA2	10	13	16	19	22	25	27	30
DGA3	13	18	23	27	33	36	41	47
DGB1	7	9	11	12	14	14	14	14
DGB2	10	13	17	20	24	26	29	33
DGB3	14	18	24	28	34	39	44	51
DGC1	9	12	14	16	19	20	21	21
DGC2	12	16	20	24	29	32	35	40
DGC3	16	21	27	32	39	43	49	56
SSA1	16	19	22	25	28	30	32	35
SSB1	13	16	19	21	24	26	28	30
SSB2	17	22	27	31	36	40	44	50
SSB3	12	15	17	19	21	22	24	25
SSC1	10	12	15	18	20	22	24	26
SSC2	12	17	22	25	30	34	38	43
SSE1	13	17	20	22	24	26	27	29
SSE2	17	22	28	32	37	41	45	50
SSE3	14	16	19	21	23	25	26	28

CHARLESTON, WEST VIRGINIA SSF (%) — 4594 DD65 (2554)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	11	15	20	23	28	31	36	42
WWB4	14	21	30	36	45	50	58	67
WWC2	14	21	29	35	43	48	55	65
TWA1	14	15	18	19	21	23	25	28
TWA2	12	15	18	21	24	27	30	35
TWA3	11	14	18	21	26	29	33	38
TWA4	10	13	18	21	26	29	34	40
TWB3	10	13	17	20	24	27	31	37
TWD4	14	20	27	32	40	45	52	61
TWE2	15	20	27	32	40	45	51	60
TWF3	8	11	15	18	22	25	29	35
TWJ2	12	18	25	30	37	42	49	58
DGA1	7	9	11	12	14	14	15	15
DGA2	10	13	16	19	24	26	30	35
DGA3	13	18	23	28	34	39	45	53
DGB1	7	9	11	12	14	15	17	18
DGB2	10	13	17	20	25	28	32	38
DGB3	13	18	24	29	36	41	47	56
DGC1	9	12	15	17	20	22	24	27
DGC2	12	16	21	24	30	34	39	46
DGC3	15	21	28	33	40	46	53	63
SSA1	17	20	24	27	32	35	39	44
SSB1	14	17	20	23	27	30	33	38
SSB2	18	23	29	34	40	45	51	59
SSB3	13	15	19	21	24	27	30	34
SSC1	10	13	16	19	23	26	30	35
SSC2	12	17	23	27	34	38	44	52
SSE1	14	18	22	26	30	33	37	42
SSE2	18	24	31	37	44	49	55	63
SSE3	14	17	20	23	26	29	32	36

MADISON, WISCONSIN SSF (%) — 7731 DD65 (4298)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	8	11	14	17	20	23	26	30
WWB4	10	16	24	29	37	42	49	58
WWC2	10	16	23	28	35	40	47	55
TWA1	12	13	14	15	17	18	19	20
TWA2	10	12	14	16	19	20	23	26
TWA3	8	11	14	16	19	21	24	28
TWA4	7	10	13	16	19	22	25	30
TWB3	8	10	13	15	18	21	24	28
TWD4	10	16	22	26	33	38	44	52
TWE2	11	16	22	26	33	37	43	51
TWF3	6	8	11	13	16	18	21	25
TWJ2	9	14	19	24	30	35	41	49
DGA1	4	5	6	7	8	8	7	6
DGA2	7	10	13	15	18	20	23	26
DGA3	11	15	19	23	28	32	38	45
DGB1	4	5	6	7	8	8	8	8
DGB2	8	10	13	15	19	21	24	29
DGB3	11	15	20	24	30	34	40	48
DGC1	6	8	10	11	13	14	15	16
DGC2	9	12	16	19	23	26	30	36
DGC3	13	17	23	27	34	39	45	55
SSA1	14	16	19	22	25	27	30	33
SSB1	11	13	16	18	21	22	25	28
SSB2	14	19	24	28	33	37	42	50
SSB3	10	12	14	16	18	19	21	23
SSC1	7	9	12	13	16	18	20	23
SSC2	9	13	18	21	27	30	35	42
SSE1	11	13	16	18	21	23	25	28
SSE2	14	19	25	29	35	39	45	52
SSE3	12	14	16	17	20	21	23	26

MILWAUKEE, WISCONSIN SSF (%) — 7445 DD65 (4139)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	8	11	14	16	20	22	25	30
WWB4	10	16	23	29	37	42	49	58
WWC2	10	16	23	28	35	40	46	55
TWA1	12	13	15	15	17	18	19	20
TWA2	10	12	14	16	18	20	22	26
TWA3	9	11	14	16	19	21	24	28
TWA4	7	10	13	15	19	22	25	29
TWB3	8	10	13	15	18	21	24	28
TWD4	10	16	21	26	33	37	43	52
TWE2	11	16	22	26	32	37	43	51
TWF3	6	8	11	13	16	18	21	25
TWJ2	9	14	19	24	30	35	40	49
DGA1	4	6	6	7	8	8	7	6
DGA2	7	10	13	15	18	20	23	26
DGA3	11	15	19	23	28	32	37	45
DGB1	4	5	6	7	8	8	8	8
DGB2	8	10	13	15	19	21	24	28
DGB3	11	15	20	24	30	34	40	48
DGC1	6	8	10	11	13	14	15	16
DGC2	9	12	16	19	23	26	30	36
DGC3	13	17	23	27	34	39	45	54
SSA1	14	17	20	22	25	27	30	34
SSB1	11	14	16	18	21	23	25	29
SSB2	15	19	24	28	34	38	43	50
SSB3	10	12	14	16	18	19	21	23
SSC1	7	9	12	13	16	18	20	23
SSC2	9	13	18	21	26	30	35	41
SSE1	11	14	16	19	21	23	26	28
SSE2	14	19	25	29	35	39	45	52
SSE3	12	14	16	18	20	22	24	26

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

SHERIDAN, WYOMING SSF (%) — 7717 DD65 (4291)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	12	17	22	26	31	35	40	47
WWB4	16	24	32	39	48	54	61	71
WWC2	16	23	31	38	46	52	59	68
TWA1	14	16	19	21	23	25	28	32
TWA2	13	16	20	23	27	30	34	40
TWA3	12	16	20	23	28	32	36	43
TWA4	11	15	20	23	29	33	37	44
TWB3	11	14	19	22	27	30	35	41
TWD4	15	22	29	35	43	48	55	65
TWE2	16	22	30	35	43	48	55	64
TWF3	9	13	17	20	25	28	33	39
TWJ2	13	20	27	32	40	46	53	62
DGA1	7	10	12	14	16	17	19	19
DGA2	10	14	18	21	26	29	33	38
DGA3	14	19	25	30	37	42	48	56
DGB1	7	10	13	15	17	19	21	23
DGB2	10	14	19	22	27	31	36	42
DGB3	14	19	26	31	38	44	51	60
DGC1	10	13	17	19	23	26	29	33
DGC2	13	17	23	27	33	37	43	51
DGC3	16	22	30	35	43	49	57	67
SSA1	17	21	25	28	33	36	40	46
SSB1	14	17	21	24	28	31	35	40
SSB2	18	24	30	35	42	46	52	60
SSB3	13	16	19	22	25	28	31	35
SSC1	11	14	18	22	26	30	34	40
SSC2	13	19	25	30	37	42	48	56
SSE1	15	19	24	27	32	35	39	44
SSE2	19	25	33	38	46	50	57	65
SSE3	15	18	21	24	28	30	34	38

SUFFIELD, ALBERTA SSF (%) — 9423 DD65 (5239)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	11	15	19	23	27	30	34	39
WWB4	14	21	29	35	44	49	56	65
WWC2	14	21	28	34	42	47	53	62
TWA1	14	15	17	19	21	23	25	28
TWA2	12	15	18	21	24	27	30	34
TWA3	11	14	18	21	25	28	32	37
TWA4	10	13	18	21	25	29	33	38
TWB3	10	13	17	20	24	27	31	36
TWD4	14	20	27	32	39	44	50	59
TWE2	14	20	27	32	39	44	50	58
TWF3	8	11	15	18	22	25	28	33
TWJ2	12	18	24	29	37	41	48	56
DGA1	7	9	11	12	13	14	15	14
DGA2	10	13	17	19	24	26	30	34
DGA3	13	18	23	28	34	38	44	51
DGB1	7	9	11	13	15	16	17	18
DGB2	10	13	17	20	25	28	32	37
DGB3	13	18	24	29	36	41	47	55
DGC1	9	12	15	17	20	22	24	26
DGC2	12	16	21	25	30	34	39	45
DGC3	15	21	28	33	40	46	52	61
SSA1	15	18	22	24	28	30	33	37
SSB1	12	15	18	21	24	26	29	32
SSB2	16	21	27	31	37	41	46	53
SSB3	11	14	16	18	21	22	24	27
SSC1	10	13	16	19	23	25	28	33
SSC2	12	17	23	27	33	37	43	50
SSE1	13	16	19	22	25	27	30	33
SSE2	16	22	28	32	39	43	48	55
SSE3	13	16	18	20	23	25	27	30

Canada

EDMONTON, ALBERTA SSF (%) — 10671 DD65 (5933)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	9	12	16	18	21	23	26	28
WWB4	11	18	25	30	37	42	48	56
WWC2	12	17	24	29	36	40	46	53
TWA1	12	14	15	17	18	19	20	22
TWA2	10	13	15	17	20	22	24	26
TWA3	9	12	15	17	20	23	25	28
TWA4	8	11	14	17	21	23	26	29
TWB3	8	11	14	17	20	22	25	28
TWD4	11	17	23	27	34	38	43	50
TWE2	12	17	23	27	33	37	42	49
TWF3	6	9	12	14	17	19	22	25
TWJ2	10	15	21	25	31	35	41	47
DGA1	5	7	8	9	9	9	9	7
DGA2	8	11	14	17	20	22	25	28
DGA3	12	16	21	25	30	34	39	45
DGB1	5	7	8	9	10	11	11	10
DGB2	8	11	15	17	21	24	27	30
DGB3	12	16	22	26	32	36	41	48
DGC1	7	9	12	13	15	17	18	18
DGC2	10	14	18	21	26	29	33	37
DGC3	14	19	25	29	36	41	46	53
SSA1	13	16	19	21	23	25	27	28
SSB1	11	13	16	17	20	21	23	25
SSB2	14	19	23	27	32	35	40	45
SSB3	10	12	14	15	17	18	18	19
SSC1	8	10	13	15	17	19	21	22
SSC2	10	14	19	23	28	31	35	40
SSE1	10	13	15	17	19	20	21	21
SSE2	13	18	23	27	32	36	40	45
SSE3	11	13	16	17	19	20	21	22

VANCOUVER, BRITISH COL. SSF (%) — 5607 DD65 (3118)

Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	15	19	24	27	31	34	37	41
WWB4	18	25	33	39	46	51	57	65
WWC2	18	25	32	38	45	49	55	62
TWA1	16	18	21	23	25	27	29	32
TWA2	15	18	22	25	28	31	34	37
TWA3	14	18	22	25	29	32	35	40
TWA4	13	17	22	25	30	33	36	41
TWB3	13	17	21	24	28	31	35	39
TWD4	17	24	31	36	43	47	53	60
TWE2	18	24	31	36	42	47	52	59
TWF3	11	15	19	22	26	29	32	37
TWJ2	16	22	29	33	40	45	50	57
DGA1	10	12	15	17	18	19	20	19
DGA2	12	16	21	24	28	31	34	37
DGA3	16	22	28	32	38	42	47	53
DGB1	10	13	16	18	20	21	22	23
DGB2	13	17	22	25	30	33	36	41
DGB3	17	22	29	33	40	45	50	57
DGC1	13	16	20	22	26	27	29	31
DGC2	15	20	25	29	35	38	42	48
DGC3	19	25	32	37	45	49	55	62
SSA1	20	23	27	30	34	36	39	42
SSB1	16	20	24	26	30	32	35	38
SSB2	21	26	32	36	42	46	51	57
SSB3	15	19	22	24	27	29	31	34
SSC1	13	17	21	23	27	29	32	35
SSC2	16	21	27	31	37	41	45	51
SSE1	18	22	26	28	32	34	36	38
SSE2	21	28	34	38	44	48	52	58
SSE3	17	20	24	26	29	31	33	36

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

WINNIPEG, MANITOBA SSF (%)					10776 DD65 (5992)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	8	10	13	16	19	21	24	28
WWB4	10	16	23	28	36	41	48	57
WWC2	10	16	22	27	34	39	45	54
TWA1	12	13	14	15	16	17	18	19
TWA2	10	11	14	15	18	20	22	25
TWA3	8	10	13	15	18	20	23	27
TWA4	7	9	13	15	18	21	24	28
TWB3	8	10	13	15	18	20	23	27
TWD4	10	15	21	25	32	37	43	51
TWE2	11	16	21	25	32	36	42	49
TWF3	5	8	10	12	15	17	20	24
TWJ2	8	13	19	23	29	34	40	47
DGA1	4	5	6	7	7	7	6	5
DGA2	7	9	12	14	18	20	22	26
DGA3	10	14	19	22	28	32	37	44
DGB1	4	5	6	7	7	8	8	7
DGB2	7	10	13	15	18	21	24	28
DGB3	11	15	19	23	29	34	39	47
DGC1	6	7	9	10	12	13	14	15
DGC2	9	12	16	19	23	26	30	35
DGC3	12	17	22	27	34	38	45	53
SSA1	12	15	17	19	22	23	26	28
SSB1	10	12	14	16	18	20	22	24
SSB2	13	17	22	25	31	34	39	46
SSB3	9	10	12	13	15	16	17	18
SSC1	6	9	11	13	15	17	19	21
SSC2	9	12	17	20	26	29	34	40
SSE1	9	11	14	15	18	19	21	22
SSE2	12	17	22	26	31	35	40	46
SSE3	11	12	14	15	17	18	20	21

HALIFAX, NOVA SCOTIA SSF (%)					7167 DD65 (3985)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	10	13	17	20	25	28	32	38
WWB4	12	19	27	33	42	47	55	64
WWC2	12	19	26	32	40	45	52	61
TWA1	13	14	16	17	19	21	23	25
TWA2	11	13	16	19	22	24	27	32
TWA3	10	13	16	19	23	26	29	35
TWA4	8	12	16	19	23	26	30	36
TWB3	9	12	15	18	22	24	28	34
TWD4	12	18	24	30	37	42	49	58
TWE2	13	18	25	30	37	42	48	57
TWF3	7	10	13	16	19	22	26	31
TWJ2	10	16	22	27	34	39	46	55
DGA1	6	7	9	10	11	11	12	11
DGA2	8	11	15	17	21	24	27	31
DGA3	12	16	21	25	32	36	42	50
DGB1	5	7	9	10	11	12	13	14
DGB2	9	12	15	18	22	25	29	34
DGB3	12	17	22	26	33	38	45	54
DGC1	7	10	12	14	16	18	20	23
DGC2	10	14	18	22	27	31	36	43
DGC3	14	19	25	30	38	43	51	60
SSA1	15	19	22	25	29	32	36	41
SSB1	13	15	19	21	25	27	30	35
SSB2	16	21	27	31	38	42	48	56
SSB3	11	14	17	19	22	24	26	30
SSC1	8	11	14	17	20	23	26	30
SSC2	11	15	21	25	31	35	41	48
SSE1	13	16	20	23	27	29	33	37
SSE2	16	22	29	34	41	46	52	59
SSE3	13	16	19	21	24	26	29	33

OTTAWA, ONTARIO SSF (%)					8461 DD65 (4704)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	8	11	14	17	20	23	26	31
WWB4	10	16	24	29	37	43	50	59
WWC2	10	16	23	28	36	41	47	56
TWA1	12	13	14	15	17	18	19	21
TWA2	10	12	14	16	19	20	23	26
TWA3	8	11	14	16	19	22	25	29
TWA4	7	10	13	16	19	22	26	31
TWB3	8	10	13	15	19	21	24	29
TWD4	10	15	22	26	33	38	44	53
TWE2	11	16	22	26	33	38	44	52
TWF3	6	8	11	13	16	18	21	26
TWJ2	9	14	19	24	31	35	41	50
DGA1	4	5	6	7	8	8	7	6
DGA2	7	10	13	15	18	20	23	27
DGA3	11	14	19	23	28	33	38	46
DGB1	4	5	6	7	8	8	9	8
DGB2	7	10	13	15	19	21	25	29
DGB3	11	15	20	24	30	34	40	49
DGC1	6	7	9	11	13	14	15	17
DGC2	9	12	16	19	24	27	31	37
DGC3	13	17	23	27	34	39	46	55
SSA1	13	16	19	21	24	26	29	33
SSB1	11	13	15	17	20	22	24	28
SSB2	14	18	23	27	33	37	42	49
SSB3	10	11	13	15	17	18	20	22
SSC1	7	9	11	13	16	18	21	24
SSC2	9	13	18	21	27	31	36	43
SSE1	10	13	16	18	21	23	25	28
SSE2	13	18	24	28	35	39	44	52
SSE3	11	13	15	17	19	21	23	25

TORONTO, ONTARIO SSF (%)					7280 DD65 (4048)			
Type	LCR = 100 (567)	70 (397)	50 (284)	40 (227)	30 (170)	25 (142)	20 (114)	15 (85)
WWA3	8	11	14	17	21	23	27	31
WWB4	10	17	24	30	38	43	50	59
WWC2	11	16	23	28	36	41	47	56
TWA1	12	13	15	16	17	18	19	21
TWA2	10	12	14	16	19	21	23	27
TWA3	9	11	14	16	20	22	25	29
TWA4	7	10	13	16	20	22	26	31
TWB3	8	10	13	16	19	21	24	29
TWD4	11	16	22	27	33	38	44	53
TWE2	11	16	22	27	33	38	44	52
TWF3	6	8	11	13	16	19	22	26
TWJ2	9	14	20	24	31	35	41	50
DGA1	5	6	7	7	8	8	8	7
DGA2	8	10	13	15	18	21	23	27
DGA3	11	15	19	23	29	33	38	46
DGB1	4	5	7	7	8	9	9	9
DGB2	8	10	13	16	19	22	25	29
DGB3	11	15	20	24	30	35	41	49
DGC1	6	8	10	11	13	14	16	17
DGC2	9	12	16	19	24	27	31	37
DGC3	13	17	23	28	34	39	46	55
SSA1	14	17	20	22	25	28	31	35
SSB1	11	14	16	18	21	23	26	29
SSB2	15	19	24	28	34	38	43	51
SSB3	10	12	14	16	18	20	22	24
SSC1	7	9	12	14	17	18	21	24
SSC2	9	13	18	22	27	31	36	43
SSE1	11	14	17	19	22	24	27	30
SSE2	14	19	25	30	36	40	46	59
SSE3	12	14	16	18	20	22	24	27

TABLE I.3 Annual Passive Heating Performance: SSF (*Continued*)

NORMANDIN, QUEBEC SSF (%)					11364 DD65 (6318)			
Type	**LCR = 100 (567)**	**70 (397)**	**50 (284)**	**40 (227)**	**30 (170)**	**25 (142)**	**20 (114)**	**15 (85)**
WWA3	6	9	11	14	17	19	21	25
WWB4	8	14	21	26	33	39	45	54
WWC2	8	14	20	25	32	36	43	51
TWA1	11	12	13	13	14	15	16	17
TWA2	8	10	12	13	16	17	19	22
TWA3	7	9	11	13	16	18	20	24
TWA4	5	8	11	13	16	18	21	25
TWB3	6	8	11	13	16	18	20	24
TWD4	8	13	19	23	30	34	40	48
TWE2	9	14	19	23	29	34	39	47
TWF3	4	6	8	10	13	15	17	20
TWJ2	7	11	17	21	27	31	37	45
DGA1	3	3	4	5	5	4	4	2
DGA2	6	8	10	13	15	17	20	23
DGA3	9	13	17	20	26	30	35	42
DGB1	3	3	4	4	5	5	5	4
DGB2	6	8	11	13	16	18	21	25
DGB3	10	13	18	21	27	31	37	45
DGC1	4	6	7	8	9	10	11	12
DGC2	8	10	14	16	20	23	27	33
DGC3	11	15	20	25	31	36	42	51
SSA1	12	14	16	18	21	23	25	27
SSB1	9	11	13	15	17	19	20	23
SSB2	12	16	21	24	30	33	38	44
SSB3	8	10	11	12	14	15	16	17
SSC1	5	7	9	11	13	14	16	18
SSC2	7	11	15	18	23	27	31	37
SSE1	8	10	13	14	16	18	19	20
SSE2	11	16	21	25	30	34	39	45
SSE3	10	11	13	14	16	17	19	20

APPENDIX J

Economic Analysis

J.1 ECONOMIC DECISION MAKING

As has been emphasized in this book, economic factors are a major consideration in almost every decision in the building design process. The discussion of economic analysis that follows is necessarily brief but covers the essential principles. For in-depth information on economic analyses of the design and construction process, see the references at the end of this appendix. Publications of the National Institute of Science and Technology (NIST; formerly The National Bureau of Standards) by Marshall and Ruegg (1980a, b) and Ruegg et al. (1978) are key sources for the following information.

The most common economic analysis questions are:

1. How can the cost of different systems *that produce the same result* be compared? This may apply to the purchase of a single item such as a motor, to the lighting of a room, or to the choice of the type of HVAC installation for an entire building. The principle involved is the same.

2. Assuming that improving a system, existing or proposed, will reduce operating costs and that many different types of improvement are possible, what preliminary economic guidelines can be established to determine whether any proposed investment appears cost-effective? Stated otherwise, how can the initial simple rate of return of a proposed investment be determined so that it can be compared to the *minimum expected rate of return* on the investment?

3. Having determined, in answering question 2, that a number of different proposals—each with its own investment and payback (savings) figures—are apparently cost-effective, how can these be compared to determine which one is *most* cost-effective? Put another way, which proposal has the maximum *net benefit or savings*? This is the type of decision that must be made when comparing energy conservation projects such as lighting control systems.

4. Having established which of the proposals is most cost-effective, how can the *actual* rate of return of the investment be determined? This figure, often referred to as *internal rate of return* (IRR), can then be compared to an expected (or required) rate of return to determine whether an investment is economically desirable.

5. What is the *payback period* of an investment? These questions are considered individually in the discussion that follows.

J.2 LIFE-CYCLE COST

Cost comparisons made on the basis of first cost are legitimate only when operating/replacement costs are nominal or hold no concern for an owner. Proposals for a concrete slab might represent the former situation, and speculative construction for immediate sale the latter. In such cases, cost comparison is simple—and based upon first cost. However, when cost comparison involves operating/maintenance/replacement costs that vary from system to system, the only reasonable way to determine and compare overall (true) system costs is by *life-cycle costing*. The basic theory and calculation techniques are well documented (see Fuller and Peterson, 1995; AIA, 1977; Marshal and Ruegg, 1980a, b; Ruegg et al., 1978), so they will be reviewed only briefly here. For discipline-specific information, see ASHRAE (2011) and IESNA (2007).

Stated simply, life-cycle cost represents the total cost of an item or system over its entire life cycle—it is the sum of the first cost and all future costs, less salvage. When the life cycle of a system being studied does not correspond to that of the building in which it is installed (as is usually the case), the designer must decide which life cycle to use. For instance, a lighting system may have an estimated life of 15 to 20 years, whereas the building life is usually at least double that figure. It is often wiser to conduct the analysis over the shorter time period, since (almost certainly) changes in technology will present an entirely different picture when the time comes to replace the system. This is true of most mechanical/electrical systems being designed today.

Life-cycle cost, in equation form, is

$$LCC = IC + MC + AC + OC \tag{J.1}$$

where

LCC = life-cycle cost
IC = investment cost (i.e., first cost minus salvage)
MC = maintenance and repair cost
AC = amortization (replacement) cost (not always included in life-cycle calculations)
OC = operating costs, including labor and energy

All costs are typically expressed in terms of present value, which is explained in this section. Costs can also be annualized. The present value approach tends to give a clearer answer to the economic decision questions posed in Section J.1. When calculating costs, the designer must include related ancillary costs. For instance, in comparing lighting systems, the costs must reflect the impact of lighting on the HVAC system (capacity and energy use) and the wiring system. For lighting system cost analysis information, see the IESNA *Lighting Handbook* (IESNA, 2011).

When the life-cycle analysis period is short—say, 2 years maximum—the last three components of Equation J.1 can be assumed to be constant without introducing an unacceptable error. For longer periods, however, this is not a valid assumption because of escalating labor and energy costs. Since these two factors weigh heavily in all economic comparisons, and since they generally apply in different proportions in the systems being considered, escalation of such costs will change the economic balance over the equipment life span. It is therefore necessary to conduct an analysis that reflects this escalation.

The present value of future payments of 1.00, made at the *end* of each of a series of n periods, is

$$PV = \frac{(1+i)^n - 1}{i(1+i)^2} \tag{J.2}$$

where

PV = present value
i = interest (discount) rate expressed as a decimal (e.g., 8% = 0.08)
n = number of periods

The factor i is more accurately the discount rate rather than the simple interest rate, the difference being that the latter reflects inflation, either actual or anticipated. If, however, the future payments escalate, the expression becomes

$$PV = \frac{1 - \left(\dfrac{K}{1+i}\right)^n}{\dfrac{1+i}{K} - 1} \tag{J.3}$$

where K is the escalation rate per period, and the remaining items are as in Equation J.2. Thus, for a 5% annual escalation, $K = 1.05$, and so on. The values of PV are tabulated in Table J.1 for interest (discount) rates of 8%, 10%, and 12% and for escalation rates of 3%, 5%, 8%, and 10%. Other values can be calculated from the equations.

It is apparent that the result of a life-cycle cost analysis depends heavily on accurate forecasting when using escalations, and that comparative results can readily shift not only with escalation estimates of the various components but also with the length of the life cycle being analyzed.

J.3 INITIAL (SIMPLE) RATE OF RETURN

This analysis addresses the second question in Section J.1: Is a proposed cost-saving investment worth examining in detail? That is, is the initial (simple) rate of return sufficient? The difference between initial and *actual* rates of return is that the former is simply

$$\text{initial rate of return} = \frac{\text{annual savings}}{\text{investment}}$$

whereas the actual (internal) rate of return depends upon the life of a project and the *total* savings accrued during the life cycle. The calculation method for the latter is given in Section J.5.

Initial rate of return is a useful criterion in that it can be very easily calculated and then compared to a *minimum* desired rate of return on investment. The *minimum* rate is emphasized, since the actual rate of return is always lower than the simple initial rate of return, except where savings escalate during the project life cycle. If a preliminary comparison indicates that the simple rate of return exceeds the minimum by a margin of a few percentage points, it is likely that a project is economically feasible, and a detailed analysis can be undertaken.

J.4 COST-EFFECTIVENESS COMPARISON

This analysis is undertaken in answer to question 3: That is, several projects are being considered, all of which meet the stated criteria. Which one is most desirable from a cost-effectiveness viewpoint? (If only one project is under consideration, the analysis proceeds directly to the IRR calculation described in the next section.)

The difference between life-cycle project cost and life-cycle project savings, that is, net lifetime savings, is a measure of cost effectiveness. Therefore, to compare the cost effectiveness of two projects, it is necessary simply to calculate this differential. This can be expressed as an equation:

$$\text{net savings} = \text{life-cycle savings} - \text{life-cycle cost}$$

Since this is true for all projects, a comparative differential can be calculated by using the differential in each term of the life-cycle cost equation, that is,

$$\Delta_{\text{net}} = \Delta_{\text{savings}} - \Delta_{\text{costs}}$$

Taking a very simple example, assume the following conditions.

	Project A	Project B
Investment	\$10,000	\$15,000
Life cycle	10 years	8 years
Annual savings	\$2,000	\$3,200
Initial rate of return	20%	32.3%
Discount rate	12%	12%

Since project B has an apparently higher rate of return, we would formulate the differential as B minus A. Using Table J.1a, the present worth of lifetime savings for project B (without escalation) is \$3200 × (4.97) or \$15,904, and that of project A is \$2000 × (5.65) or \$11,120. Therefore, the differential cost benefit (CB) of B minus A is

$$\Delta_{\text{life savings}} \text{ minus } \Delta_{\text{project costs}}$$

or

$$\begin{aligned} \Delta_{CB} &= (\$15{,}904 - \$11{,}120) - (\$15{,}000 - \$10{,}000) \\ &= \$4784 - \$5000 = -\$216 \end{aligned}$$

indicating that project A is more cost-effective despite the apparently higher rate of return of project B. If we include escalation in costs, the life savings of the longer-life project (A) will shrink more than the savings of shorter-life project B. Using Table J.1d, the projects are about equal, with 3% annual escalation. With higher rates of escalation, project B is more cost-effective.

J.5 INTERNAL RATE OF RETURN (IRR)

Internal rate of return represents the rate of return at which lifetime savings are exactly equal to lifetime costs. IRR cannot be calculated directly, but only by trial and error. Assume a rate of return, calculate the present value (PV) of savings, and compare PV to lifetime costs. Because of this difficulty, IRR is frequently neglected, and initial rate of return is used instead, although, as discussed in Section J.4, this can readily give misleading results. To illustrate the calculation of IRR, return to the very simple example in Section J.4 and calculate IRR for projects A and B.

For project A, a present worth factor of \$10,000/\$2000 = 5 is needed, in 10 years. Referring to Table J.1a, note that at a discount (interest) rate of 15%, the present worth factor is 5.019, indicating that IRR is slightly above this level. (It is actually 15.1%.) For project B an 8-year present worth factor of \$15,000/\$3200, or 4.69, is needed. Referring again to Table J.1a, note that this factor falls between 12% and 15%. A series of trials with Equation J.2 will eventually arrive at 13.7%, which is 1.4% *less* than the same factor for project A, confirming the conclusion reached in Section J.4.

J.6 PAYBACK PERIOD

The payback period referred to in most proposals is the reciprocal of the initial rate of return and is usually referred to as the *simple* payback period. However, just as the actual rate of return differs from the simple rate (and is usually *lower*), the actual or *discount* payback period is different from, and usually *longer* than, the simple one. This period is, logically, the period of time required for the accumulated net savings to equal the initial investment, with all figures expressed in present value dollars. To illustrate, return to the example given in Section J.4.

1. *Proposal A.* As in the IRR calculation, a present worth factor of \$10,000/\$2000, or 5, is needed at a 12% discount rate. From Table J.1a, find this to be about 8.1 years. This compares to a simple payback period of 5 years. Note that this is *not* the reciprocal of IRR.
2. *Proposal B.* Here a present worth factor of \$15,000/\$3200, or 4.7, is needed. At a 12% discount rate, from Table J.1a, this is about 7.3 years. This compares to a simple payback period of 4.7 years.

TABLE J.1*a* Present Value of *n* Future Payments Beginning at the End of the First Period

	Interest (Discount) Rate per Period						
n	6%	8%	10%	12%	15%	20%	25%
1	0.94	0.93	0.91	0.89	0.87	0.83	0.80
2	1.83	1.78	1.74	1.69	1.63	1.53	1.44
3	2.67	2.58	2.49	2.40	2.28	2.11	1.95
4	3.47	3.31	3.17	3.04	2.86	2.59	2.36
5	4.21	3.99	3.79	3.61	3.35	2.99	2.69
6	4.92	4.62	4.36	4.11	3.78	3.33	2.95
7	5.58	5.21	4.87	4.56	4.16	3.61	3.16
8	6.21	5.75	5.34	4.97	4.49	3.84	3.33
9	6.80	6.25	5.76	5.33	4.77	4.03	3.46
10	7.36	6.71	6.15	5.65	5.02	4.19	3.57
11	7.89	7.14	6.50	5.94	5.23	4.33	3.66
12	8.83	7.54	6.81	6.19	5.42	4.44	3.73
13	8.85	7.90	7.10	6.42	5.58	4.53	3.78
14	9.30	8.24	7.37	6.63	5.72	4.61	3.82
15	9.71	8.56	7.61	6.81	5.85	4.68	3.86
16	10.11	8.85	7.82	6.97	5.95	4.73	3.89
17	10.48	9.12	8.02	7.12	6.05	4.78	3.91
18	10.83	9.37	8.20	7.25	6.13	4.81	3.93
19	11.16	9.60	8.37	7.37	6.20	4.84	3.94
20	11.47	9.82	8.51	7.47	6.26	4.87	3.95
21	11.76	10.02	8.65	7.56	6.31	4.89	3.96
22	12.04	10.20	8.77	7.65	6.36	4.91	3.97
23	12.30	10.37	8.88	7.72	6.40	4.93	3.98
24	12.55	10.53	8.99	7.78	6.43	4.94	3.98
25	12.78	10.68	9.08	7.84	6.46	4.95	3.99

TABLE J.1*b* Present Value of n Future Payments Beginning at the End of the First Period and Escalating at *K* per Period—8% Discount

	Interest (Discount) Rate per Period 8%			
	Annual (Periodic) Escalation Rate K			
n	**1.03**	**1.05**	**1.08**	**1.10**
1	0.95	0.97	1.00	1.02
2	1.86	1.92	2.00	2.06
3	2.73	2.84	3.00	3.11
4	3.56	3.73	4.00	4.19
5	4.35	4.60	5.00	5.28
6	5.10	5.44	6.00	6.40
7	5.82	6.26	7.00	7.54
8	6.50	7.06	8.00	8.70
9	7.15	7.84	9.00	9.88
10	7.78	8.59	10.00	11.08
11	8.37	9.33	11.00	12.30
12	8.94	10.04	12.00	13.55
13	9.48	10.73	13.00	14.82
14	9.99	11.41	14.00	16.11
15	10.48	12.06	15.00	17.43
16	10.95	12.70	16.00	18.77
17	11.40	13.32	17.00	20.13
18	11.82	13.92	18.00	21.53
19	12.23	14.51	19.00	22.94
20	12.62	15.08	20.00	24.39
21	12.99	15.63	21.00	25.86
22	13.34	16.17	22.00	27.35
23	13.68	16.69	23.00	28.88
24	14.00	17.20	24.00	30.43
25	14.30	17.69	25.00	32.01

TABLE J.1*c* Present Value of *n* Future Payments Beginning at the End of the First Period and Escalating at *K* per Period—10% Discount

	Interest (Discount) Rate per Period 10%			
	Annual (Periodic) Escalation Rate K			
n	**1.03**	**1.05**	**1.08**	**1.10**
1	0.94	0.96	0.98	1.00
2	1.81	1.87	1.95	2.00
3	2.63	2.74	2.89	3.00
4	3.40	3.57	3.82	4.00
5	4.12	4.36	4.73	5.00
6	4.80	5.12	5.63	6.00
7	5.43	5.84	6.51	7.00
8	6.02	6.53	7.37	8.00
9	6.57	7.18	8.22	9.00
10	7.09	7.81	9.05	10.00
11	7.58	8.41	9.87	11.00
12	8.03	8.98	10.67	12.00
13	8.46	9.53	11.46	13.00
14	8.85	10.05	12.23	14.00
15	9.23	10.55	12.99	15.00
16	9.58	11.27	13.74	16.00
17	9.90	11.48	14.47	17.00
18	10.21	11.91	15.19	18.00
19	10.50	12.32	15.90	19.00
20	10.76	12.72	16.59	20.00
21	11.02	13.09	17.27	21.00
22	11.25	13.45	17.94	22.00
23	11.47	13.80	18.59	23.00
24	11.68	14.12	19.24	24.00
25	11.87	14.44	19.87	25.00

TABLE J.1*d* Present Value of *n* Future Payments Beginning at the End of the First Period and Escalating at *K* per Period—12% Discount

	Interest (Discount) Rate per Period 12%			
	Annual (Periodic) Escalation Rate K			
n	**1.03**	**1.05**	**1.08**	**1.10**
1	.92	.94	.96	.98
2	1.77	1.82	1.89	1.95
3	2.54	2.64	2.79	2.89
4	3.26	3.41	3.66	3.82
5	3.92	4.14	4.49	4.74
6	4.52	4.82	5.29	5.64
7	5.08	5.45	6.07	6.52
8	5.59	6.05	6.82	7.38
9	6.06	6.61	7.54	8.23
10	6.49	7.13	8.23	9.07
11	6.89	7.63	8.90	9.89
12	7.26	8.09	9.55	10.69
13	7.59	8.52	10.17	11.49
14	7.90	8.92	10.77	12.26
15	8.19	9.30	11.35	13.03
16	8.45	9.66	11.91	13.78
17	8.69	9.99	12.45	14.51
18	8.91	10.31	12.97	15.23
19	9.11	10.60	13.47	15.95
20	9.30	10.87	13.95	16.64
21	9.47	11.13	14.42	17.34
22	9.63	11.37	14.87	18.00
23	9.78	11.60	15.30	18.66
24	9.91	11.81	15.72	19.31
25	10.04	12.01	16.12	19.95

Note from these results the very important fact that a shorter payback period does not necessarily indicate a more cost-effective investment. Here, proposal A has a better return precisely because it yields good savings for a longer period. Summing up the results of the simple study, we have:

	Project A	Project B
Initial rate of return	20%	21.3%
Internal rate of return	15.1%	13.7%
Simple payback period	5 years	4.7 years
Discounted payback period	8.1 years	7.3 years

This shows very clearly that although initial rate of return and simple payback are indications of a proposal's value, they are useless in comparative studies.

REFERENCES

AIA. 1977. *Life Cycle Cost Analysis—A Guide for Architects.* American Institute of Architects. Washington, DC.

ASHRAE. 2011. *ASHRAE Handbook—HVAC Applications*, Chapter 39. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Fuller, S. K. and S. R. Peterson. 1995. *Life-Cycle Costing Manual for the Federal Energy Management Program.* National Institute of Standards and Technology. Gaithersburg, MD. http://fire.nist.gov/bfrlpubs/

IESNA. 2011. *Lighting Handbook*, 10th ed., Chapter 18. Illuminating Engineering Society of North America. New York, NY.

Marshall, H. E. and R. T. Ruegg. 1980a. *Energy Conservation in Buildings: An Economics Guidebook for Investment Decision.* National Bureau of Standards Handbook 132. NBS. Washington, DC.

Marshall, H. E. and R. T. Ruegg. 1980b. *Simplified Energy Design Economics.* National Bureau of Standards Special Publication 544. NBS. Washington, DC.

Ruegg, R. T., et al. 1978. *Life-Cycle Costing.* National Bureau of Standards Publication 113. NBS. Washington, DC.

APPENDIX K

Sound Transmission Data

K.1 SOUND TRANSMISSION DATA FOR WALLS

To use these data:

1. Find the desired wall construction Type Code in Table K.1.
2. Find the desired STC corresponding to the selected wall construction Type Code.
3. Refer to Table K.3 for details of wall construction to confirm that the choice is reasonable.
4. Refer to Table K.2 for wall thickness, weight, STC, fire rating, and the transmission losses at standard octave midpoints.

EXAMPLE

An interior masonry partition with an STC between 50 and 55 is desired. Of particular interest is the TL at 1000 Hz.

1. From Table K.1, find Type Code "c."
2. From Table K.1, note that constructions W6, W12b, W15b, and W22b are acoustically suitable for the proposed use.
3. From consideration of the information in Table K.3, decide that construction W15b is most suitable for the proposed use.
4. From Table K.2, find that construction W15b has a transmission loss of 55 dB at 1000 Hz.

TABLE K.1 Sound Transmission Class: Walls

Type Code:		
a. Wooden stud	**e. Staggered stud**	**i. Absorbent blankets or fill**
b. Metal stud	**f. Plaster**	**j. Fiber board**
c. Masonry	**g. Gypsum wallboard**	**k. Lead**
d. Concrete	**h. With resilient element**	**l. Gypsum core board**

STC	Type	Item No.	STC	Type	Item No.
63	d,f	W4	46	a,f	W30a
62[a]	c,f,j,m	W23	46	a,f	W31a
56	c	W7	46	a,f,k	W31c
56[a]	c,f	W8	46	a,e,g,i	W37
55[a]	b,g,i	W63	45	c,d	W10b
54[a]	c,f,m	W22b	45	a,f,i	W38
54	b,f,h	W52	45	b,f,h	W50a
53[a]	d,f	W2	45	g,l,m	W85a
53	c,f,h	W15b	44	c	W12a
52[a]	c,f	W6	44	a,e,g	W34a
51	b,f	W44a	44	a,e,g	W35a
51	b,g,h,i	W67	44	a,f,h	W40a
50	c,k	W12b	43	c,d	W10a
50	b,g,i	W60	43[a]	d,j,m	W21
50	g,i,l,m	W85b	43	a,e,f	W35a
49[a]	c,f,m	W22a	43	a,e,f	W36a
48	c,d	W9	43	b,f,k	W43b
48	a,e,f,i	W36b	42[a]	c,f	W5
48	b,f,k	W43c	42	a,f	W14a
47	d	W1	41	b,f	W43a
47	a,g,k	W28b	41	b,g	W55a
47	a,f,k	W31b	40	c,f	W13
47	a,g,h	W39a	40	a,g	W32a
46	c,f	W11a	39	a,g	W28a
46	c,f,h	W15a	36	g,l	W80

[a]Field measurement.

Source: All data extracted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD/FHA/NBS 1971. U.S. Department of Housing and Urban Development, Washington, DC.

TABLE K.2 Sound Transmission Loss: Walls

Designation	Thickness in. (mm)	Weight lb/ft^2 (kg/m^2)	Transmission Loss (dB) at frequency 125	250	500	1K	2K	4K	STC	Fire Rating (hr)
W1	3 (76)	39 (190)	35	40	44	52	58	64	47	½
W2	7 (178)	80 (390)	39	42	50	58	64	—	53	3
W4	≈ 16 (406)	184 (898)	50	54	59	65	71	68	63	4+
W5	5½ (140)	55 (268)	34	34	41	50	66	—	42	2.5
W6	10 (254)	100 (488)	41	43	49	55	57	—	52	4+
W7	12 (305)	121 (590)	45	45	53	58	60	61	56	4+
W8	25 (635)	280 (1366)	50	53	52	58	61	—	56	4+
W9	12 (305)	79 (386)	46.5	44	46	52	54	56	48	4
W10a	6 (152)	34 (166)	32	33	40	47	51	48	43	1
W10b	6 (152)	34 (166)	37	36	42	49	55	58	45	1
W11a	5¼ (133)	35.8 (175)	36	37	44	51	55	62	46	2
W12a	3¾ (133)	26.1 (127)	40	40	40	48	55	56	44	1.5
W12b	5 (127)	31 (151)	41	46	46	56	63	67	50	1.5
W13	4 (102)	21.5 (105)	39	34	38	43	48	46	40	3
W14a	5 (127)	23.4 (114)	37	42	39	44	49	49	42	4
W15a	5 (127)	27 (132)	38	37	44	51	56	59	46	3
W15b	6 (152)	31 (151)	45	44	50	55	56	59	53	4
W20	7 (178)	22.9 (112)	32	46	49	53	58	66	52	3
W21	10¼ (260)	37 (181)	41	42	46	51	52	—	43	Not available
W22a	12 (305)	100 (488)	37	41	48	60	60.5	—	49	4+
W22b	12 (305)	100 (488)	40	44	55	67.5	70	—	54	4+
W23	18 (457)	120 (586)	48	54	58	64	69	—	62	4+
W28a	5 (127)	6 (29)	21	28	35	42	45	41	39	0.5
W28b	≈ 5⅛ (130)	12 (58)	27	37	43	52	56	—	47	0.5
W30a	5¾ (146)	13.4 to 15.7 (65 to 77)	32	37	42	47	47	63	46	0.75
W31a	5¾ (146)	13.4 to 15.7 (65 to 77)	32	37	42	48	48	63	46	0.75
W31b	≈ 5⅞ (149)	—	33	41	45	52	55	65	47	0.75
W31c	≈ 5⅞ (149)	17–19 (83-93)	32.5	40	43	47	50	62	46	0.75
W32a	5½ (140)	8.2 (40)	27	31	39	45	52.5	48	40	1
W34a	5 (127)	6.2 (30)	36	36	40	47	52	45	44	0.5
W35a	6½ (165)	13.4 (65)	41	41	46	49	41	54	44	1.5
W35b	5¾ (146)	15.6 (76)	48	46	48	48	48	59	43	1
W36a	6¼ (159)	11.1 (54)	36	33	42	42	41	51	43	0.75
W36b	6¼ (159)	12.8 (62)	37	37	49	50	52	66	48	1
W37	5¾ (146)	13.8 (67)	39	40	42	47.5	55	51.5	46	0.5
W38	5⅜ (137)	14.2 (69)	39	45	48	50	44	54	45	1
W39a	6¼ (159)	6.7 (33)	30	40	46	50	49	49	47	1
W40a	≈ 6½ (165)	14.4 (70)	43	41	48	50	42	56	44	1
W43a	3⅜ (86)	12.3 (60)	27	37	43	46	39	47	41	0.75
W43b	3½ (89)	15.2 (74)	35	43	45	47	48	58	43	0.75
W43c	≈ 3½ (89)	18.2 (89)	36	45	47	50	53	61	48	0.75
W44a	5 (127)	15.7 (77)	34	38	47	50	52	58	51	1
W50a	5¼ (133)	13 (63)	35	46	48	51	48	43	45	0.75
W52	5 (127)	19 (93)	50	52	55	56	52	60	54	1
W55a	4⅞ (124)	6 (29)	29	36	40	46	40	46	41	1
W60	3½ (89)	5.4 (26)	34	40	47	50	53	54	50	1
W63	6⅛ (156)	11.5 (56)	36	47	51	57	57	62	55	2
W67	6½ (165)	11.3 (55)	41	46	49	51	50	60	51	2
W80	2¼ (57)	10.2 (50)	34	34	37	38	39	45	36	1
W85a	5⅛ (130)	14.6 (71)	36	35	45	51	53	57	45	3
W85b	6 (152)	12.8 (62)	37	37	54	56	56	62	50	3

Source: All data extracted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD/FHA/NBS 1971. U.S. Department of Housing and Urban Development, Washington, DC. SI units added by text authors (not part of original source).

TABLE K.3 Construction Characteristics of Walls (for other data, see Table K.2)

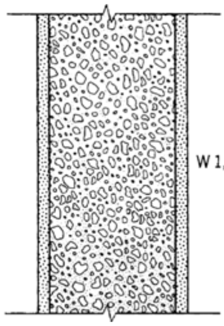
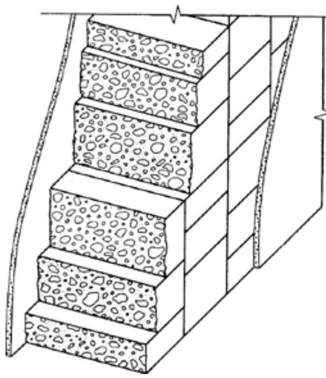
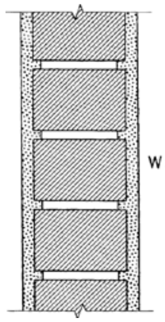
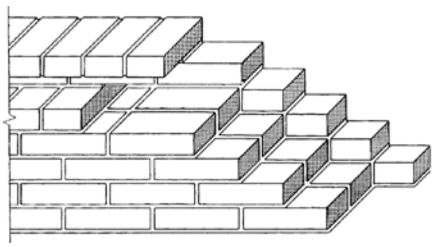
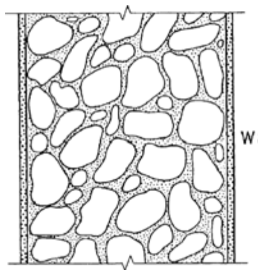
Designation	Description	Section Sketch
Solid Concrete		
W1	3-in.-thick (76-mm) solid concrete wall poured in situ in test opening. All surface cavities were sealed with thin mortar mix.	 W1, W2
W2	6-in.-thick (152-mm) concrete wall with ½-in.-thick (13-mm) layer of plaster on both sides.	
W4	Wall of 4, 6, and 8 × 8 × 16 in. (102, 152, 204 × 204 × 406 mm) sand and gravel aggregate solid concrete blocks; on each side, ¼- to ½-in.-thick (6- to 13-mm) layer of cement gypsum plaster and sand.	 W4
W5	4½-in.-thick (114-mm) brick wall with ½-in.-thick (13-mm) layer of plaster on each side.	 W5, W6
W6	9-in.-thick (229-mm) brick wall with ½-in.-thick (13-mm) layer of plaster on each side.	
W7	12-in.-thick (305-mm) brick wall.	 W7
W8	24-in.-thick (610 mm) stone wall with ½-in.-thick (13-mm) layer of plaster on both sides.	 W8

TABLE K.3 Construction Characteristics of Walls (for other data, see Table K.2) (*Continued*)

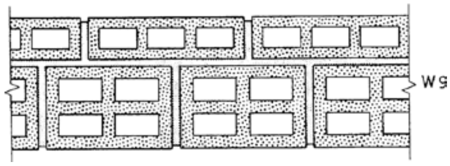
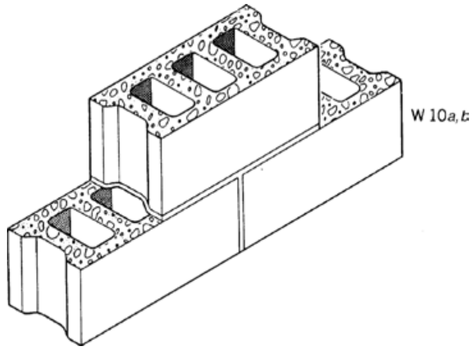
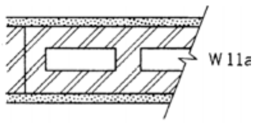
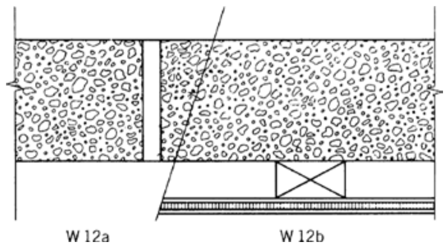
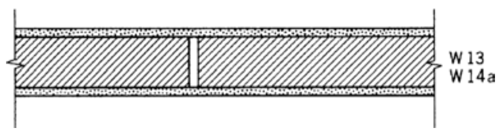
Designation	Description	Section Sketch
Hollow Concrete Block		
W9	12-in. (305-mm) wall made of hollow 8 × 8 × 12 in. (204 × 204 × 305 mm) and 8 × 4 × 16 in. (204 × 102 × 406 mm) concrete blocks.	
W10a	6-in. (152-mm) hollow concrete blocks constructed with vertical mortar joints staggered.	
W10b	Similar to W10a except wall painted.	
Cinder Block		
W11a	4 × 8 × 16-in. (102 × 204 × 406-mm) hollow cinder blocks; on each side, ⅝ in. (16 mm) of sanded gypsum plaster.	
Cement Block		
W12a	3⅝ × 7¾ × 13½-in. (92 × 197 × 343-mm) lightweight-aggregate cement blocks with ½-in. (13-mm) mortar joints; three coats of masonry paint applied to each side of partition.	
W12b	Same as W12a, except that 1 × 2-in. (25 × 50-mm) furring strips were nailed vertically to partition on one side; 1/16-in. (1.5-mm) layer of lead, 3.94 lb/ft^2 (19.2 kg/m^2), nailed to furring strips, ¼-in. (6-mm) plywood-covered lead with joints caulked.	
Hollow Gypsum Block		
W13	3-in. (76-mm) hollow gypsum blocks cemented together with ⅜-in. (10-mm) mortar joints; on each side, ½-in. (13-mm) sanded gypsum plaster.	
W14a	4-in. (102-mm) hollow gypsum blocks cemented together with ⅜-in. (10-mm) mortar joints; on each side, ½-in. (13-mm) sanded gypsum plaster.	

TABLE K.3 Construction Characteristics of Walls (for other data, see Table K.2) (*Continued*)

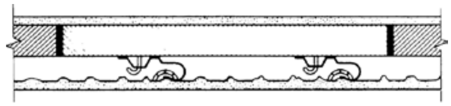
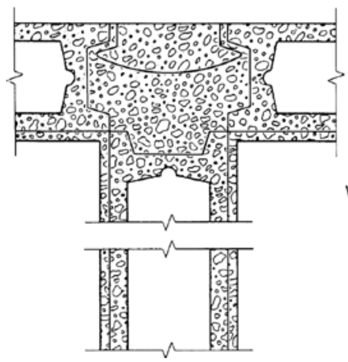
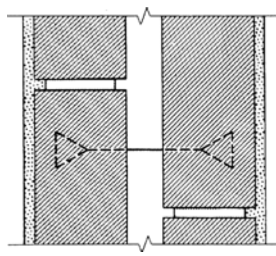
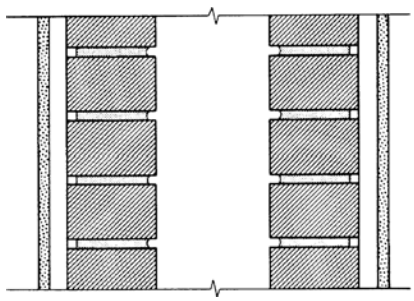
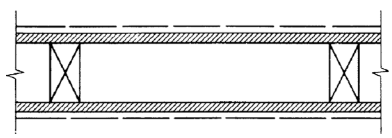
Designation	Description	Section Sketch
Hollow Gypsum Block, Resilient on One Side, Plaster on Both Sides		
W15a	3 × 12 × 30-in. (76 × 305 × 762-mm) hollow gypsum blocks with ½-in. (13-mm) mortar joints. On one side, 7/16-in. (11-mm) sanded gypsum plaster; on the other side, resilient clips, spaced 18 in. (457 mm) apart on centers vertically and 16 in. (406 mm) apart on centers horizontally, held to ¾-in. (19-mm) metal channels 16 in. (406 mm) on centers, to which expanded metal lath was wire-tied; 1 1/16-in. (27-mm) sanded gypsum plaster; 1/16-in. (1.5-mm) white-coat finish applied to both sides.	 W 15a,b
W15b	Similar to W15a except that 4 × 12 × 30-in. (102 × 305 × 762 mm) gypsum blocks were used.	
Hollow Concrete		
W21	Precast concrete hollow wall panels with in situ concrete posts and beams. Panels have 1½-in.-thick (38-mm) concrete shells with 6¼-in. (159-mm) air space between them. Layer of fiberboard ½ in. (13 mm) thick is adhered to the exposed surfaces of the panel.	 W 21
Double Walls		
W22a	Double wall with 4½-in.-thick (114-mm) brick leaves separated by a 2-in. (50-mm) cavity (wire ties between leaves); ½-in. (13-mm) plaster on exposed sides.	 W 22
W22b	Similar to W22a but no wire ties between the leaves.	
W23	Double wall with 4½-in.-thick (114-mm) brick leaves, 6-in. (152-mm) cavity (no ties); on exposed sides, ½-in. (13-mm) plaster on 1-in.-thick (25-mm) wood-wool slabs mortared to the brick walls.	 W 23
Wood Stud Walls		
W28a	2 × 4-in. (50 × 100-mm) wooden studs, 16 in. on (406 mm) centers, ½-in. (13-mm) gypsum wallboard nailed to each side. All joints taped and finished.	 W 28a,b
W28b	Similar to W28a except that a layer of lead, 2.95 lb/ft^2 (14.4 kg/m^2), was laminated to each side of the panel.	

TABLE K.3 Construction Characteristics of Walls (for other data, see Table K.2) (*Continued*)

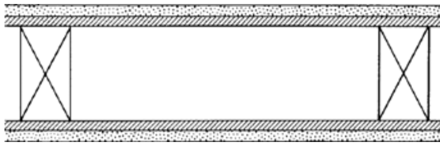
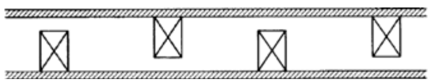
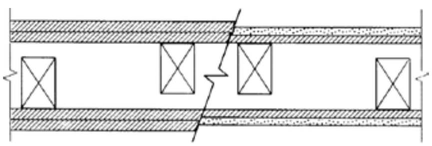
Designation	Description	Section Sketch
W30a	2 × 4-in. (50 × 100-mm) wooden studs, 16 in. (406 mm) on centers, attached to 2 × 4-in. (50 × 100-mm) wooden floor and ceiling plates, ⅜-in. (10-mm) gypsum lath nailed to studs on both sides, ½-in. (13-mm) sanded plaster with white-coat finish.	
W31a	2 × 4-in. (50 × 100-mm) wooden studs, 16 in. (406 mm) on centers, ⅜-in. (10-mm) gypsum lath nailed to studs on both sides, ½-in. (13-mm) sanded plaster with white-coat finish.	
W31b	Similar to W31a except that a 0.065-in.-thick (1.7-mm) layer of lead weighing 3.85 lb/ft^2 (18.8 kg/m^2) was laminated to each side of the panel.	
W31c	Similar to W31a except that a 0.13-in.-thick (3.3-mm) layer of lead weighing 7.9 lb/ft^2 (38.5 kg/m^2) was laminated to one side of the panel.	
W32a	2 × 4-in. (50 × 100-mm) wooden studs, 16 in. (406 mm) on centers; on each side, two layers of ⅜-in. (10-mm) gypsum wallboard were cemented together; joints in exposed surfaces taped and finished.	
Staggered Wood Stud Walls		
W34a	2 × 3-in. (50 × 75-mm) wooden studs, 16 in. (406 mm) on centers, staggered 8 in. (203 mm) on centers, attached to 2 × 4-in. (50 × 100-mm) wooden plates at ceiling and floor; ½-in. (13-mm) gypsum wallboard nailed 7 in. (178 mm) on centers on both sides to studs. All joints taped and finished.	
W35a	2 × 3-in. (50 × 75-mm) wooden studs, 16 in. (406 mm) on centers, staggered 8 in. (203 mm) on centers (attached to 2 × 4-in. (50 × 100-mm) wooden plates at floor and ceiling); two layers of ⅝-in. (16-mm) tapered-edge gypsum wallboard, first layer nailed 7 in. (178 mm) on centers, second layer nailed 16 in. (406 mm) on centers. All exposed joints taped and finished.	
W35b	Similar to W35a except that the wall was constructed with ⅜-in. (10-mm) perforated gypsum lath and ½-in. (13-mm) sanded gypsum plaster with white-coat finish.	

TABLE K.3 Construction Characteristics of Walls (for other data, see Table K.2) (*Continued*)

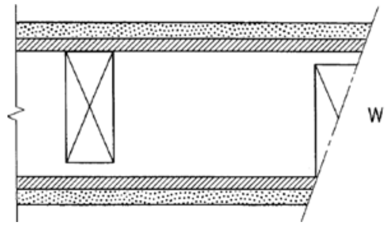
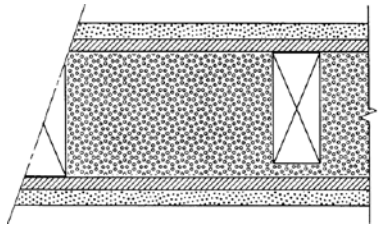
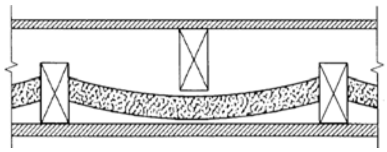
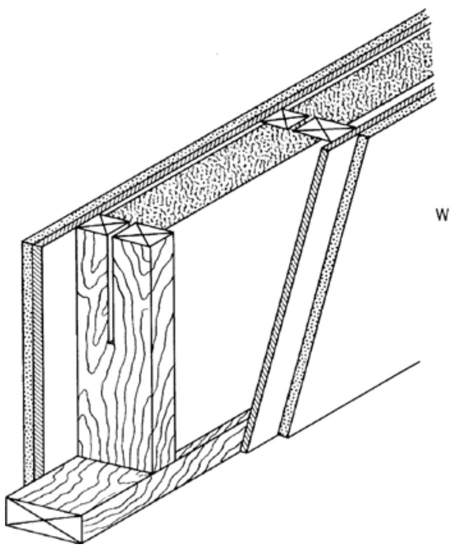
Designation	Description	Section Sketch
W36a	2 × 4-in. (50 × 100-mm) wooden studs, 16 in. (406 mm) on center, staggered 8 in. (203 mm) on center and offset ½ in. (13 mm). On each side, ⅜-in. (10-mm) gypsum lath nailed to studs, ½-in. (13-mm) gypsum vermiculite plaster, machine applied, and a hand-applied white-coat finish.	
W36b	Same as W36a except that the space between the studs contained vermiculite fill with a density of 6.3 lb/ft^3 (101 kg/m^3).	
W37	2 × 4-in. (50 × 100-mm) wooden studs, 16 in. (406 mm) on center, staggered 8 in. (203 mm) on center, attached to a 2 × 4¾-in. (50 × 120-mm) wooden floor and ceiling plates; ½-in. (13-mm) gypsum wallboard nailed on both sides to studs, 0.9-in. (23-mm) wood-fiber wool blanket stapled on the inside of one side of the wall. All joints taped and finished.	
Slotted Wood Studs		
W38	2 × 4-in. (50 × 100-mm) slotted wooden studs, 16 in. (406 mm) on centers, attached to 2 × 4-in. (50 × 100-mm) wooden floor and ceiling plates; ⅜-in. (10-mm) gypsum lath nailed 7 in. (178 mm) on center to studs, ½-in. (13-mm) gypsum plaster with white-coat finish applied to both sides. 3-in. (75-mm) mineral fiber batts stapled between studs.	

TABLE K.3 Construction Characteristics of Walls (for other data, see Table K.2) (*Continued*)

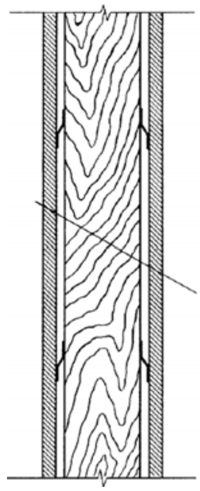
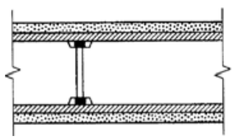
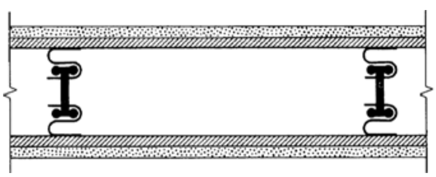
Designation	Description	Section Sketch
Wood Studs; Resilient Mounting		
W39a	2 × 4-in. (50 × 100-mm) wooden studs, 16 in. (406 mm) on centers, attached to 2 × 4-in. (50 × 100-mm) wooden floor and ceiling plates; resilient channels nailed horizontally to both sides of studs 24 in. (610 mm) on center, ⅝-in. (16-mm) gypsum wallboard screwed 12 in. (305 mm) on center to channels. All joints taped and finished.	 W 39a
W40a	2 × 4-in. (50 × 100-mm) wooden studs, 16 in. (406 mm) on center; resilient clips, nailed to studs on both sides, held ⅜-in. (10-mm) gypsum lath, ½-in. (13-mm) sanded gypsum plaster with white-coat finish.	 W 40a
Steel Truss Stud Wall		
W43a	1⅝-in. (41-mm) steel truss studs; ⅜-in. (10-mm) gypsum lath, ½-in. (13-mm) plaster on both sides.	 W 43*a, b, c* W 44*a*
W43b	Similar to W43a except that a layer of lead, 2.95 lb/ft^2 (14.4 kg/m^2), was laminated to one side of the partition.	
W43c	Similar to W43a except that a layer of lead, 2.95 lb/ft^2 (14.4 kg/m^2), was laminated to each side of the partition.	
W44a	3¼-in. (83-mm) steel truss studs, 24 in. (610 mm) on center, attached to metal floor and ceiling tracks; on both sides, ⅜-in. (10-mm) perforated gypsum lath attached with wire clips wire-tied to studs, ½-in. (13-mm) sanded gypsum plaster.	
Steel Truss Studs; Resilient Mounting		
W50a	2½-in. (64-mm) steel truss studs 16 in. (406 mm) on center, ⅜-in. (10-mm) gypsum lath attached with resilient clips to studs, ½-in. (13-mm) plaster applied to both sides.	 W 50a

TABLE K.3 Construction Characteristics of Walls (for other data, see Table K.2) (*Continued*)

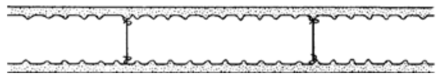
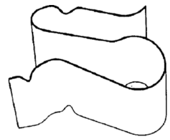
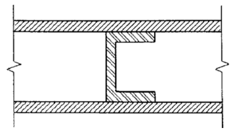
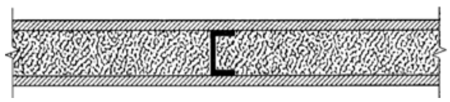
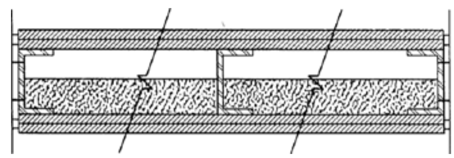
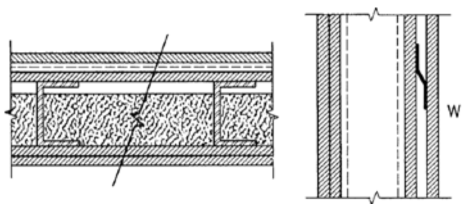
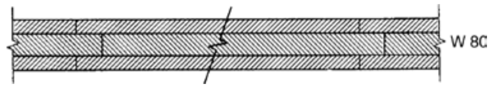
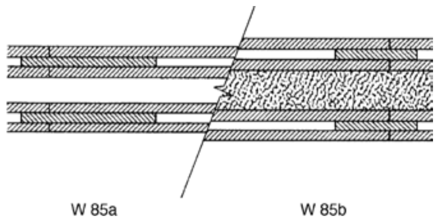
Designation	Description	Section Sketch
W52	3¼-in. (83-mm) steel truss studs, 16 in. (406 mm) on center; on each side, resilient clips fastened 16 in. (406 mm) on center to studs, ¼-in. (6-mm) metal rod wire-tied to clips, diamond mesh metal lath wire-tied to metal rods, ¾-in. (19-mm) sanded gypsum plaster.	 
Metal Channel Stud Wall		
W55a	3⅝-in. (92-mm) metal channel studs, 24 in. (610 mm) on center, set into 3⅝-in. (92-mm) metal floor and ceiling runners; ⅝-in. (16-mm) gypsum wallboard screwed to studs on both sides. All joints taped and finished.	
W60	2½-in. (64-mm) metal channel studs, 24 in. (610 mm) on center, set in 2½-in. (64-mm) metal floor and ceiling runners; ½-in. (13-mm) vinyl-coated gypsum wallboard adhesively attached and screwed to studs on both sides. All joints sealed with caulking compound. Aluminum batten strips screwed 12 in. (305 mm) on center to gypsum board at joints; top and bottom finished with aluminum ceiling and base trim. 2-in. (50-mm) mineral fiber blankets hung between studs.	
W63	3⅝-in. (92-mm) metal channel studs, 24 in. (610 mm) on center, set into 3⅝-in. (92-mm) metal runners, which were attached through continuous beads of nonsetting resilient caulking compound to floor and ceiling, respectively. Two layers of ⅝-in. (16-mm) gypsum wallboard attached to both sides of studs. First layer screwed 8 in. (203 mm) on center at joints and 12 in. (305 mm) on center in field; second layer laminated and screwed 24 in. (610 mm) on center to first layer, with joints staggered 24 in. (610 mm). 1½-in.-thick (38-mm) mineral fiber felt, 3 lb/ft^3 (48 kg/m^3), stapled between studs. All exposed joints taped and finished. The ¼-in. (6-mm) clearance around the perimeter closed with a nonsetting resilient caulking compound.	
W67	3⅝-in. (92-mm) metal channel studs, 24 in. (610 mm) on center, set in 3⅝-in. (92-mm) metal floor and ceiling runners; ⅝-in. (16-mm) gypsum wallboard screwed to studs on both sides. On one side, resilient channels screwed horizontally, 24 in. (610 mm) on center to inner layer; ⅝-in. (16-mm) gypsum wallboard screwed to channels. On the other side, ⅝-in. (16-mm) gypsum wallboard laminated directly to inner layer. 3-in. (75-mm) mineral fiber blankets hung between studs. All exposed joints taped and finished.	

TABLE K.3 Construction Characteristics of Walls (for other data, see Table K.2) (*Continued*)

Designation	Description	Section Sketch
Gypsum Partitions		
W80	24-in.-wide (610-mm) panels constructed of 1 × 24-in. (25 × 610-mm) gypsum core board offset 1½ in. (38 mm) at edges to form tongue-and-groove edge; ⅝-in. (16-mm) vinyl-faced gypsum wallboard laminated to both sides of core board. Panels inserted into two-piece metal floor and ceiling tracks. Gypsum-to-gypsum screws at ¼ and ½ points along vertical edges of face boards.	
W85a	Double wall with 1⅜-in. (35-mm) air space. Each leaf consisted of 24-in.-wide (610-mm) panels of ⅝-in. (16-mm) gypsum core board strips, 7½ and 4⅜ in. (191 and 111 mm) wide, offset 1½ in. (38 mm) at edges to form tongue and groove; ⅝-in. (16-mm), vinyl-faced, gypsum wallboard laminated to both sides of core board strips. Panels screwed 12 in. (305 mm) on center to 1¼ × 1-in. (32 × 25-mm) angle floor and ceiling runners.	
W85b	Similar to W85a except that space between leaves was 2⅛ in. (54 mm) and contained 2-in. (50-mm) mineral fiber blankets stapled to one leaf. ¼-in. (6-mm) perimeter clearance closed with a nonsetting resilient caulking compound. Vertical face layer joints sealed with joint compound.	

Source: All data extracted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD/FHA/NBS 1971. U.S. Department of Housing and Urban Development, Washington, DC. SI units added by text authors (not part of original source).

K.2 SOUND TRANSMISSION AND IMPACT INSULATION DATA FOR FLOOR/CEILING CONSTRUCTIONS

To use these data:

1. Find the desired construction Type Code in Table K.4 or K.5. Table K.4 lists constructions by sound transmission class (STC). Table K.5 lists constructions by impact insulation class (IIC).
2. Find desired STC/IIC ratings corresponding to the selected Type Code.
3. Refer to Table K.7 for details of construction to confirm appropriateness of selection.
4. Refer to Table K.6 for thickness, weight, STC, IIC, fire rating, and transmission loss at standard octave midpoints.

EXAMPLE

A standard wooden joist floor-ceiling construction is desired. The assembly must have a minimum IIC of 55; any STC above 35 is acceptable.

1. Since IIC is the determining factor, refer to Table K.5. The basic Type Code is "a."
2. From Table K.5, note that none of the listed "a" constructions gives an IIC of 55. However, from Section 24.24 of the text, note that the addition of carpeting will add 10 to 27 points to the IIC, making items F34, F38a, F39a, and F30 all suitable. This approach avoids special and resilient constructions in order to comply with the requirement for standard (i.e., simple) construction.
3. From Table K.7, select construction F30 as being most appropriate for the application of carpeting.
4. From Table K.6 find (without carpet): thickness 9½ in. (240 mm), STC 34, IIC 32 (+ carpet), fire rating ¼ hour. With high-pile carpeting on a foam rubber pad, this construction will have an IIC > 55, STC > 35.

TABLE K.4 Sound Transmission Class: Floor/Ceiling Constructions

Type Code

- **a. Wooden joist**
- **b. Metal joist**
- **c. Concrete or masonry**
- **d. Plaster ceiling**
- **e. Gypsum board ceiling**
- **f. With resilient elements**
- **h. With carpeting**
- **i. With absorbent blankets**
- **j. With separate ceiling joists**

STC	IIC	Type	Item No.	STC	IIC	Type	Item No.
55[a]	57[a]	c,d,f	F14	46[a]	42[a]	c,d	F23
54[a]	64[a]	c,d,f	F17b	45	44	a,e,f	F44
52	80	a,e,i,j	F48	44	42	c,f	F3-2d
51[a]	53[a]	c,d ,f	F10	44	41	c	F3-1a
51[a]	48[a]	c,d	F7a	44	80	c,h	F2-1a
50[a]	53[a]	c,e,f	F25	44	29	c	F1-c
50[a]	51[a]	c,e	F27	44	25	c	F1a
50[a]	48[a]	c,d	F16	43[a]	43[a]	a,d	F32b
49[a]	48[a]	c,d	F9	42[a]	32[a]	c	F22
48[a]	47[a]	c,d	F12	40	32	a,e,i	F40a
48	33	b,c,d	F60a	39[a]	37[a]	a,e	F34
47	62	b,c,e	F58	37	33	a,e	F38a
47[a]	42[a]	c,d	F24	37	32	a,e	F39a
47	59	b,c,d,h	F57b	34[a]	32[a]	a,e	F30
47	37	b,c,d	F57a	29[a]	32[a]	a,e	F35a
46	74	b,c,d	F60c	29	56	a,e,h	F35b

[a]Field measurement.

TABLE K.5 Impact Insulation Class: Floor/Ceiling Constructions

Type Code							
a. Wooden joist				**f. With resilient ceiling element**			
b. Metal joist				**g. With resilient floor element**			
c. Concrete or masonry				**h. With carpeting**			
d. Plaster ceiling				**i. With absorbent blankets**			
e. Gypsum board ceiling				**j. With separate ceiling joists**			
IIC	**STC**	**Type**	**Item No.**	**IIC**	**STC**	**Type**	**Item No.**
80	52	a,e,h,i,j	F48	44	45	a,e,f	F44
80	44[b]	c,h	F2-1a	43[a]	43[a]	a,d,g	F32b
74	46	b,c,d,h	F60c	42[a]	47[a]	c,d	F24
64[a]	54[a]	c,d,g	F17b	42[a]	46[a]	c,d	F23
62	47	b,c,e,h	F58	42	44[b]	c,g	F3-2(d)
59	47[b]	b,c,d,h	F57b	41	44[b]	c	F3-1(a)
57[a]	55[a]	c,d,g	F14	37	47	b,c,d	F57a
56[a]	29[b]	a,e,h	F35b	37[a]	39[a]	a,e	F34
53[a]	51[a]	c,d,g	F10	33	48	b,c,d	F60a
53[a]	50[a]	c,e,g	F25	33	37	a,e	F38a
51[a]	50[a]	c,e	F27	32[a]	42[a]	c	F22
48[a]	51[a]	c,d	F7a	32	40	a,e,i	F40a
48[a]	50[a]	c,d	F16	32	37	a,e	F39a
48[a]	49[a]	c,d,g	F9	32[a]	34[a]	a,e	F30
47[a]	48[a]	c,d	F12	32[a]	29[a]	a,e	F35a
				29	44[b]	c	F1c
				25	44	c	F1a

[a]Field measurement.
[b]Estimated on the basis of similar structures.

TABLE K.6 Floor/Ceiling Sound Transmission and Construction Data

Designation	Thickness in. (mm)	Weight lb/ft^2 (kg/m^2)	*Transmission Loss (dB) at frequency* 125	250	500	1K	2K	4K	STC	IIC	Fire Rating (hr)
F1a	4 (102)	53 (259)	47	42	45	56	58	66	44	25	1
F7a	5¼ (134)	61 (298)	41	42	47	54	59	63	51	48	2
F9	6⅝ (168)	65 (317)	40	42	46	48	57	62	49	48	2
F10	8¼ (210)	90 (439)	38	43	47	53	60	—	51	53	2½
F12	10 (254)	62 (303)	38	40	44	51	56	59	48	47	3
F14	9½ (242)	83 (405)	38	44	52	55	60	—	55	57	3
F16	8⅛ (206)	65 (317)	40	42	46	52	58	—	50	48	2
F17b	9¼ (235)	57 (278)	38	46	52	59	64	—	54	64	2
F22	6¼ (158)	28 (137)	34	34	38	45	55	61	42	32	¾
F23	9½ (242)	45 (220)	33	37	43	52	58	62	46	42	¾
F24	10¼ (260)	65 (317)	34	37	43	52	57	—	47	42	¾
F25	10 (254)	45 (220)	30	38	46	58	64	—	50	53	¾
F27	7⅝ (194)	50 (244)	36	40	47	54	58	—	50	51	¾
F30	9½ (242)	7 (34)	19	24	31	35	45	—	34	32	¼
F32b	11 (280)	12 (59)	30	31	41	47	52	—	43	43	¾
F34	10¼ (260)	9.9 (48)	15	32	44	48	54	53	39	37	1
F35a	10 (254)	9.2 (45)	14	17	30	44	47	52	29	32	—
F38a	11¾ (298)	9 (44)	30	38	36	43	48	49	37	33	½
F39a	11⅞ (302)	9.5 (46)	22	32	36	45	49	56	37	32	1
F40a	11⅞ (302)	10 (49)	25	36	38	46	51	57	40	32	1
F44	10½ (266)	10.1 (49)	43	41	41	52	50	60	45	44	¾
F48	12⅜ (314)	10.7 (52)	35	42	52	56	69	74	52	80	¾
F57a	18 9⁄16 (472)	23.2 (113)	33	44	45	46	58	62	47	37	3
F58	21½ (546)	20.4 (100)	27	37	45	54	60	65	47	62	1
F60a	11 (280)	38.2 (186)	42	44	44	51	51	61	48	33	1½
F60c	11⅝ (295)	39 (190)	39	43	44	52	52	65	46	74	—

Source: Material extracted from *A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings*, HUD/FHA/NBS, 1971. U.S. Department of Housing and Urban Development, Washington, DC. SI units added by text authors (not part of original source).

TABLE K.7 Construction Characteristics of Floor Types

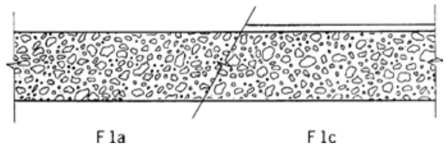
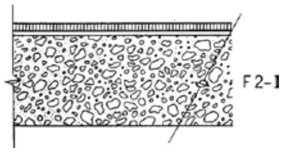
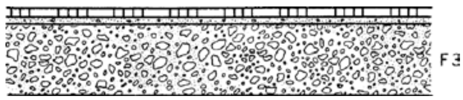
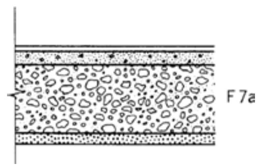
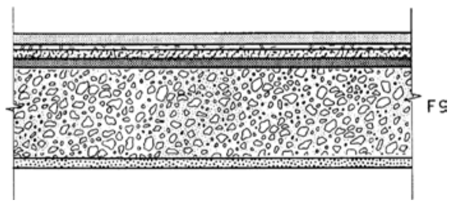
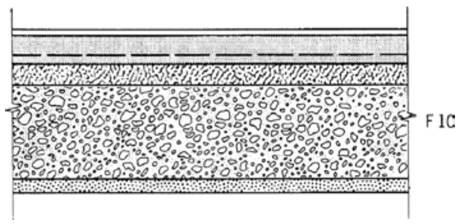
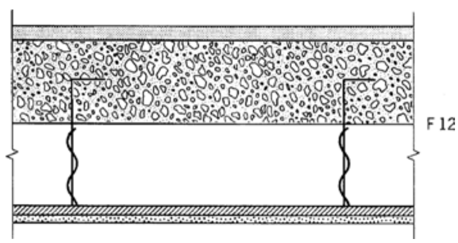
Code	Description	Section Sketch
Reinforced Concrete Slab		
F1a	4-in.-thick (100-mm) reinforced concrete slab, isolated from support structure. Concrete was reinforced with 6 × 6-in. No. 6 AWG reinforcing mesh (150 × 150 at 4 mm) placed at the centerline horizontal plane of the slab. All surface cavities were sealed with a thin mortar mix.	
F1c	Same as F1a except that ⅛-in.-thick (3-mm) vinyl tile was adhered to concrete.	
Reinforced Concrete with Floor Coverings		
See also F1c above.		
F2-1(a)	4-in.-thick (100-mm) reinforced concrete slab with carpeting and pad. The carpeting was of ¼-in. (6-mm) wool loop pile with ⅛-in. (3-mm) woven jute backing, 0.49 lb/ft^2 (2.4 kg/m^2); the foam rubber pad was ¼ in. (6 mm) thick and weighed 0.53 lb/ft^2 (2.6 kg/m^2).	
F3-1(a)	4-in. (100-mm) reinforced concrete slab with ½ × 9 × 9-in. (13 × 230 × 230 mm) oak blocks, 1.8 lb/ft^2 (8.8 kg/m^2), set in mastic.	
F3-2(d)	4-in. (100-mm) concrete slab with ⅛-in. (3-mm) cork.	
F7a	4⅜-in.-thick (111-mm) reinforced concrete slab. On the floor side, ¾-in.-thick (19-mm) sand-cement screed with ⅛-in. (3-mm) linoleum floor covering. On the ceiling side, ⅜-in. (10-mm) layer of plaster.	
F9	4⅜-in.-thick (111-mm) reinforced concrete slab. On the floor side, ½-in.-thick (13-mm) layer of bitumen with ½-in.-thick (13-mm) soft wood fiberboard, which was covered with a thin layer of bitumen with sand and a ¾-in.-thick (19-mm) sand-cement screed. On the ceiling side, ⅜-in. (10-mm) layer of plaster.	
Reinforced Concrete Slab, Floating Floor		
F10	5-in.-thick (127-mm) reinforced concrete. On the floor side, 1½-in.-thick (38-mm) wire mesh reinforced sand-cement screed floating on ½-in.-thick (13-mm) bitumen-bonded, glass-wool quilt covered with building paper. On the screed, ½-in.-thick (13-mm) pitch-mastic with a linoleum floor covering. On the ceiling side,½-in. (13-mm) layer of plaster.	
F12	4⅜-in.-thick (111-mm) reinforced concrete slab. On the floor side, ¾-in.-thick (19-mm) sand-cement screed. On the ceiling side, brick wire mesh, suspended 4 in. (100 mm) with wire hangers, held ⅞-in. (22-mm) gypsum plaster.	

TABLE K.7 Construction Characteristics of Floor Types *(Continued)*

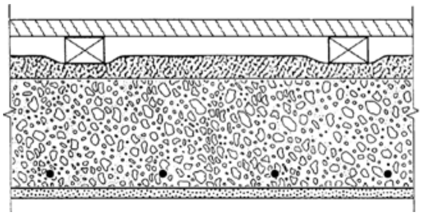
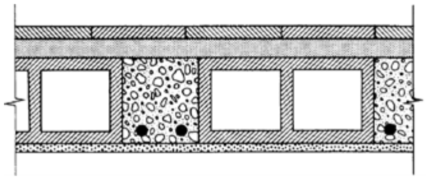
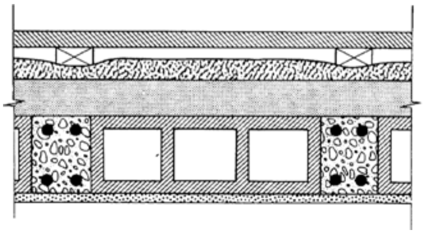
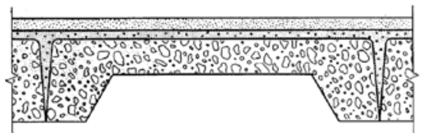
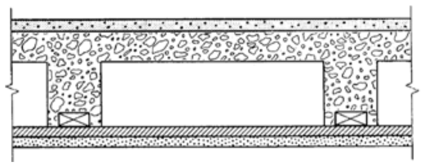
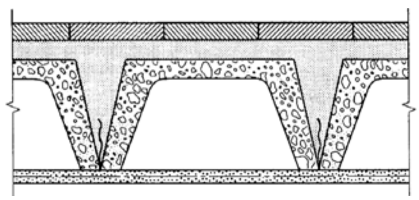
Code	Description	Section Sketch
F14	6-in.-thick (152-mm) reinforced concrete slab. On the floor side, ¾-in.-thick (19-mm) tongue-and-groove wood flooring nailed to 1½ × 2-in. (38 × 50 mm) wooden battens, 16 in. (406 mm) on centers, floating on 1-in.-thick (25-mm) glass-wool quilt. On the ceiling side, ½-in. (13-mm) layer of plaster.	 F 14
Concrete with Hollow Blocks		
F16	5 × 10-in. (127 × 254-mm) hollow masonry blocks, 14 in. (356 mm) on center, with spaces between blocks filled with 5-in.-thick (127-mm) reinforced concrete. On the floor side, ⅞-in.-thick (22-mm) wood blocks adhered to 1½-in.-thick (38-mm) sand-cement screed. On the ceiling side, ¾-in. (19-mm) layer of plaster.	 F 16
F17b	4 × 12½-in. (100 × 318-mm) hollow masonry blocks, 15½ in. (394 mm) on center, with spaces between blocks filled with 4-in.-thick (100-mm) reinforced concrete. On the floor side, 2-in.-thick (50-mm) sand-cement screed; linoleum on 1-in.-thick (25-mm) wood flooring nailed to 1 × 2-in. (25 × 50-mm) wooden battens, spaced 15½ in. (394 mm) on centers, floating on a glass-wool quilt approximately 1 in. (25 mm) thick. On the ceiling side, ¾-in. (19-mm) layer of plaster.	 F 17b
Concrete Channel Slab		
F22	Prefabricated concrete channel slabs mortared together 20 in. (508 mm) on center. Each slab had a 3-in.-deep (76-mm) trapezoidal channel with bases of 11 and 14¾ in. (280 and 75 mm). On the floor side, ¾-in.-thick (19-mm) sand-cement finish.	 F 22
Ribbed Concrete		
F23	7¼-in. (184-mm) ribbed concrete floor. Ribs were 5¼ × 3¾ in. (133 × 95 mm), spaced 21 in. (533 mm) on center, with 1 × 2-in. (25 × 50 mm) wooden nailing strips cast into ends. On the floor side, the slab was 2 in. (50 mm) thick with a ¾-in.-thick (19-mm) sand-cement screed. On the ceiling side, ⅝-in.-thick (16-mm) wooden laths nailed to nailing strips held ⅝-in.-thick (16-mm) plaster.	 F 23
Concrete Channel Beam		
F24	7-in. (178-mm) precast trapezoidal concrete channel beams, 14 in. (356 mm) on center, with spaces between beams filled with sand-cement mix. On the floor side, 1½-in.-thick (38-mm) sand-cement screed with 1-in.-thick (25-mm) wood-block floor covering. On the ceiling side, approximately ¾-in.-thick (19-mm) layer of plaster on expanded metal lath.	 F 24

TABLE K.7 Construction Characteristics of Floor Types *(Continued)*

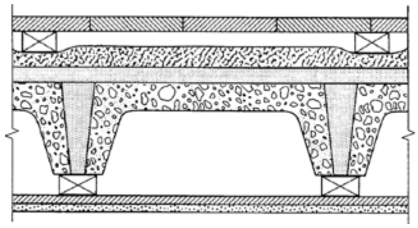
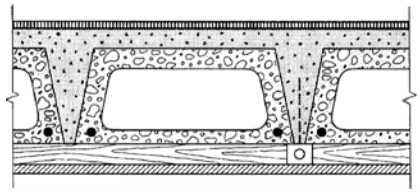
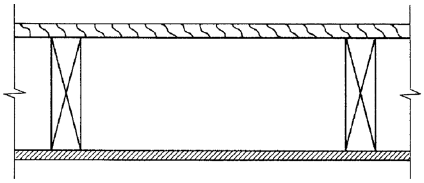
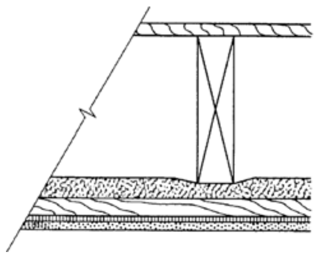
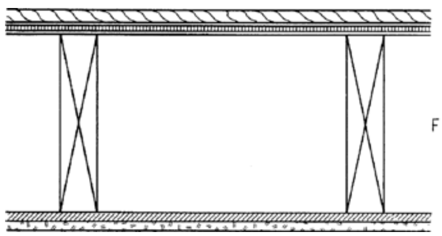
Code	Description	Section Sketch
Precast Concrete Beam, Floating Floor		
F25	5-in. (127-mm) precast concrete channel beams, 14½ in. (368 mm) on center, with spaces between beams filled with a sand-cement mix. On the floor side, ⅞-in.-thick (22-mm) tongue-and-groove wood flooring nailed to 1 × 2-in. (25 × 50-mm) wooden battens, 20 in. (508 mm) on center, on approximately 1-in.-thick (25-mm) glass-wool quilt on ¾-in.-thick (19-mm) sand-cement screed. On the ceiling side, ⅛-in. (3-mm) layer of plaster on ⅜-in. (10-mm) gypsum wallboard nailed to 1 × 2-in. (25 × 50-mm) wooden battens spaced 14½ in. (368 mm) on centers.	 F 25
Hollow Concrete Beam		
F27	5-in. (127-mm) precast trapezoidal hollow concrete beams, 14½ in. (368 mm) on center, with bases of 14 and 12½ in. (256 and 318 mm). Spaces between beams filled with sand-cement mix. On the floor side, 1-in.-thick (25-mm) sand-cement screed with 3⁄16-in. (5-mm) cork tile floor covering. On the ceiling side, ⅜-in.-thick (10-mm) gypsum wallboard attached to 1 × 2- in. (25 × 50-mm) wooden battens held by metal clips.	 F 27
Wooden Joist		
F30	2 × 8-in. (50 × 200-mm) wooden joists, 16 in. (406 mm) on center. On the floor side, ⅞-in. (22-mm) tongue-and-groove flooring nailed to joists; on the ceiling side, ⅜-in. (10-mm) gypsum wallboard nailed to joists with joints sealed.	 F 30
F32	2 × 8-in. (50 × 200-mm) wooden joists 18 in. (457 mm) on center. On the floor side, ⅞-in. (22-mm) tongue-and-groove wood flooring nailed to joists. On the ceiling side, 1-in. (25-mm) battens nailed through glass-wool quilt approximately 1 in. (25 mm) thick; ½-in. (13-mm) layer plaster on ¼-in.-thick (6-mm) wood lath.	 F 32
F34	2 × 8-in. (50 × 200-mm) wooden joists, 16 in. (406 mm) on center. On the floor side, ½-in.-thick (13-mm) C-D plywood nailed 8 in. (203 mm) on center to joists, 25⁄32-in.-thick (20-mm) hardwood flooring on plywood. On the ceiling side, ½-in.-thick (13-mm) gypsum wallboard nailed 6 in. (152 mm) on center to joists. All joints taped and finished; ceiling tile adhered to gypsum board.	 F 34

TABLE K.7 Construction Characteristics of Floor Types *(Continued)*

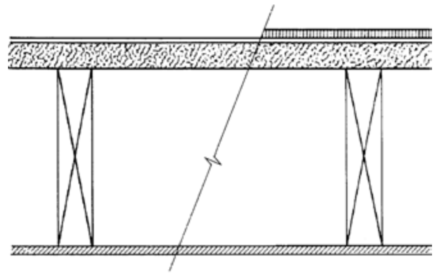
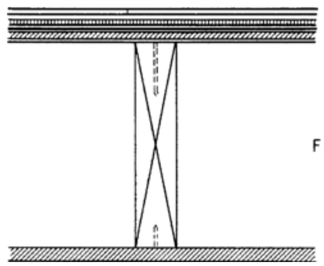
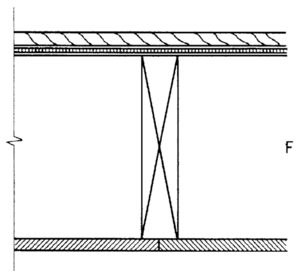
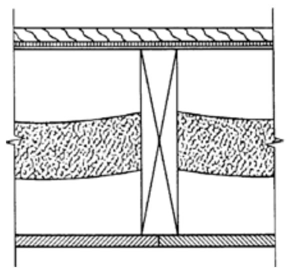
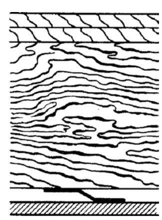
Code	Description	Section Sketch
F35a	2 × 8-in. (50 × 200-mm) wooden joists, 16 in. (406 mm) on center. On the floor side, 1½-in.-thick (38-mm) tongue-and-groove wood fiberboard nailed to joists, vinyl tile floor covering. On the ceiling side, ½-in.-thick (13-mm) gypsum wallboard nailed 6 in. (152 mm) on center to joists. All joints taped and finished.	 F 35a F 35b
F35b	Similar to F35a except that fiberboard was covered with carpet and pad.	
F38a	2 × 10-in. (50 × 250-mm) wooden floor joists spaced 16 in. (406 mm) on center. ⅝-in. (16-mm) fir plywood subfloor nailed to joists 8 in. (203 mm) on center; ½-in. (13-mm) plywood underlayment nailed to subfloor with joints staggered to miss joints of the subfloor; ⅛ × 9 × 9-in. (3 × 230 × 230-mm) vinyl asbestos tile glued to underlayment. On the ceiling side, ½-in. (13-mm) gypsum wallboard nailed 12 in. (305 mm) on center, with all joints and nailheads taped and finished.	 F 38a
F39a	2 × 10-in. (50 x 250-mm) wooden joists, 16 in. (406 mm) on center. On the floor side, ½-in.-thick (13-mm) plywood subfloor nailed 6 in. (152 mm) on center along edges and 10 in. (254 mm) on center in field, building paper underlayment, $\frac{25}{32}$ × 2¼-in. (20 × 57-mm) oak wood flooring nailed at each joist intersection and midway between joists. On the ceiling side, ⅝-in.-thick (16-mm) gypsum wallboard, nailed 6 in. (152 mm) on center to joists. All joints taped and finished.	 F 39a
Wooden Joist with Insulation		
F40a	2 × 10-in. (50 × 250-mm) wooden joists 16 in. (406 mm) on center with 3-in.-thick (76-mm) mineral fiber batts stapled between joists. On the floor side, ½-in.-thick (13-mm) plywood subfloor nailed 6 in. (152 mm) on center along edges and 10 in. (254 mm) on center in field, building paper underlayment, $\frac{25}{32}$ × 2¼-in. (20 × 57-mm) oak wood flooring nailed at each joist intersection and midway between joists. On the ceiling side, ⅝-in.-thick (16-mm) gypsum wallboard nailed 6 in. (152 mm) on center to joists. All joints taped and finished.	 F 40a
Wooden Joist, Resilient Ceiling		
F44	2 × 8-in. (50 × 200-mm) wooden joists 16 in. (406 mm) on center. On the floor side, ¾-in.-thick (19-mm) wood subfloor, layer of building paper, and ¾-in.-thick (19-mm) tongue-and-groove fir finish flooring. On the ceiling side, resilient runners bridged across joists and nailed 12 in. (305 mm) on center to joists; ⅝-in.-thick (16-mm) gypsum wallboard screwed to resilient runners. All joints taped and finished.	F 44 

TABLE K.7 Construction Characteristics of Floor Types *(Continued)*

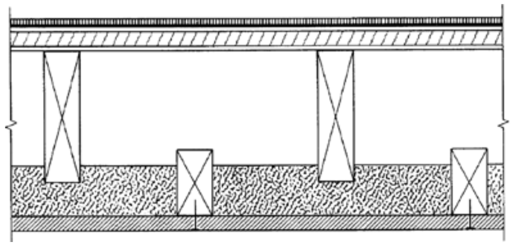
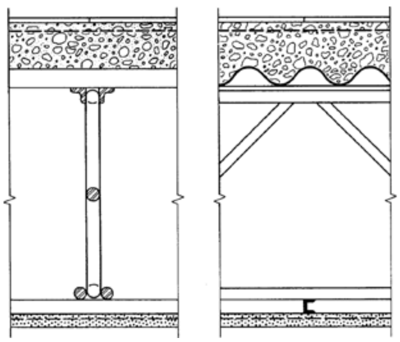
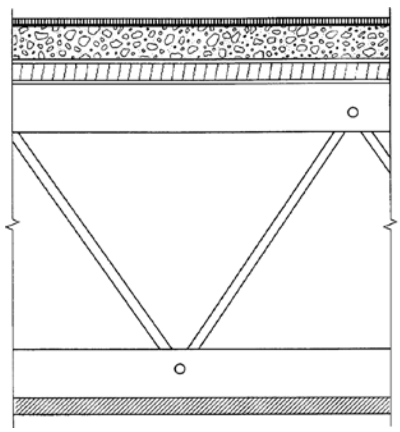
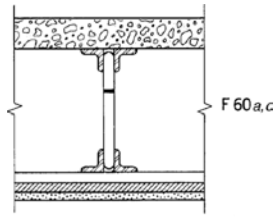
Code	Description	Section Sketch
F48	2 × 8-in. (50 × 200-mm) wooden joists, 16 in. (406 mm) on center. On the floor side, 1⅛-in.-thick (29-mm) regular C-D rough plywood nailed 6 in. (152 mm) on center along periphery and 16 in. (406 mm) on center at other bearings, plywood covered with an all-hair pad at 40 oz/yd^2 (1356 g/m^2) and all-wool pile at 44 oz/yd^2 (1492 g/m^2) carpet. The total weight of the carpet was 4.14 lb/yd^2 (2.25 kg/m^2) and the total thickness was ⅜ in. (10 mm). On the ceiling side, 2 × 4-in. (50 × 100-mm) wooden joists, 16 in. (406 mm) on center, staggered 8 in. (203 mm) on center relative to the floor joists, 3-in.-thick (76-mm) fibered glass blankets stapled between ceiling joists, ⅝-in.-thick (16-mm) gypsum wallboard nailed to ceiling joists. All joints taped and finished; entire periphery of panel caulked and sealed. The ceiling was supported independently of the floor structure.	 F 48
Steel Joist with Concrete Floor		
F57a	2½-in.-thick (64-mm) perlite concrete, 72 lb/ft^3 (152 kg/m^3) on 28-gauge (0.39-mm) corrugated steel units supported by 14-in. (356-mm) steel bar joists; ⅛-in.-thick (3-mm) asphalt tile cemented to concrete. On the ceiling side, ¾-in. (9-mm) furring channels, 13½ in. (343 mm) on center, wire-tied to joists, 3.4 lb/yd^2 (1.85 kg/m^2) diamond mesh metal lath wire-tied to furring channels, 9⁄16-in. (14-mm) coat of plaster with 1⁄16-in. (1.6-mm) white-coat finish.	 F 57a,b
F57b	Same as F57a except for carpet and pad in lieu of asphalt tile.	
F58	18-in. (457-mm) steel joists, 16 in. (406 mm) on center. On the floor side, ⅝-in.-thick (16-mm) C-D rough plywood nailed to joists, 1⅝- in.-thick (41-mm) foamed concrete, 100 lb/ft^3 (1600 kg/m^3), slab constructed on the plywood; concrete covered with an all-hair pad at 40 oz/yd^2 (1356 g/m^2) and an all-wool pile at 44 oz/yd^2 (1492 g/m^2) carpet. Total weight of the carpet, 4.14 lb/yd^2 (2.25 kg/m^2); total thickness, ⅜ in. (10 mm). On the ceiling side, ⅝- in.-thick (10-mm) gypsum wallboard nailed to joists. All joints taped and finished; entire periphery of panel caulked and sealed.	 F 58

TABLE K.7 Construction Characteristics of Floor Types *(Continued)*

Code	Description	Section Sketch
F60a	7-in. (178-mm) steel bar joists spaced 27 in. (686 mm) on center. On the floor side, ⅜-in. (10-mm) metal rib lath attached to top of joists and 2-in.-thick (50-mm) poured concrete floor. On the ceiling side, ¾-in. (19-mm) metal furring channels wire-tied to joists 16 in. (406 mm) on centers; ⅜ × 16 × 48-in. (10 × 406 × 1220-mm) plain gypsum lath held with wire clips and sheet metal end joint clips; 7⁄16-in. (11-mm) sanded gypsum plaster and 1⁄16-in. (1.6-mm) white-coat finish.	
F60c	Structure F60a with nylon carpeting and foam rubber pad placed on the floor. The carpet pad had an uncompressed thickness of ¼ in. (6 mm) backed with a woven jute fiber cloth. The carpet had ⅛-in. (3-mm) woven backing and ¼-in. (6-mm) looped pile spaced 7 loops per inch with a total thickness of ⅜ in. (10 mm).	

Source: Material extracted from *A Guide to Airborne, Impact and Structure-Borne Noise Control in Multifamily Dwellings*, HUD/FHA/NBS, 1971. U.S. Department of Housing and Urban Development, Washington, DC. SI units added by text authors (not part of original source).

APPENDIX L

Design Analysis Software

This book presents numerous manual (or hand) calculation procedures for a variety of systems. These methods are simple enough to require only a calculator and an informed and patient user. This emphasis comes from the belief that such calculations provide the most explicit means of understanding the variables (and relationships among variables) that influence building performance. In practice, however, many analyses are conducted using computer software programs.

Intriguingly, such software (in a quest for accuracy) often involves variables that are not intuitive to the building designer. This is particularly true in the area of building envelope thermal analysis. When things are non-intuitive they can quickly become mysterious. Mystery variables that affect building design are not good. Building design is an art and science—but the building science part cannot be opaque to the designer. Much of the high-end analysis software available today is also unforgiving for inputs such as "properties not yet determined." Such variables are common during schematic design (who knows the infiltration leakage rate of a window during the first few weeks of design—when a usable estimate of building performance may be crucial to decision making?). Time will tell how some of these contradictions work out in the next generations of software.

Personal computers (including laptops) are capable of running (even if sometimes slowly) most commonly used building systems analysis programs. This appendix presents a very short list (drawn from a larger and rapidly expanding array) of such programs that may be used in the design of mechanical and electrical systems (both passive and active) for buildings. Two points to bear in mind: Updated and improved versions of existing programs appear often, as do new programs, and any listing of such programs quickly becomes obsolete. Thus, the descriptions presented here avoid version numbers and other transient information, instead describing the basics of each program. Mailing addresses are generally included; current URLs are provided where applicable.

Apologies to those researchers whose programs do not appear here; the following list attempts to compile the programs most widely used (or readily available) in North America.

L.1 COMMONLY USED BUILDING SYSTEMS ANALYSIS PROGRAMS

(a) Building Products Life-Cycle Assessment

- BEES (**B**uilding for **E**nvironmental and **E**conomic **S**ustainability): This program aids in the selection of building products by generating an overall score. It weighs the environmental and economic life-cycle performance scores, with relative scales specified by the user. Global warming, acidification, nutrification, natural resource depletion, IAQ, and solid waste impacts are included.

  http://www.nist.gov/el/economics/BEESSoftware.cfm

(b) Design Strategies and Climate Analysis

- Climate Consultant: Accepting readily available climate data files, this program plots an array of user-selected climate analyses for every hour of the year, using a variety of charting techniques (and provides commentary).
  http://www.energy-design-tools.aud.ucla.edu/
- Green Building Advisor: Provide a project location, building type, and size, and this program responds with "moderately" and "strongly" suggested design strategies, relevant case studies, an information library, and a products directory. This is a tool for brainstorming rather than for making detailed design decisions.
  Environmental Building News, 28 Birge St., Suite 30, Brattleboro, VT 05301
- Solar-2: Graphically displays the performance of a window with any combination of fins and overhang, as well as remote objects such as walls of an exterior courtyard or a distant building.
  http://www.energy-design-tools.aud.ucla.edu/

(c) Heating, Cooling, and Energy Performance

- Building Energy Software Tools Directory: An extensive online directory of software tools, compiled by the U.S. Department of Energy. Well worth browsing.
  http://apps1.eere.energy.gov/buildings/tools_directory/
- BEopt: Tool for balancing and optimizing high-performance building strategies with cost-saving goals, in order to establish affordable energy-efficiency strategies for a proposed building. It is applicable to both new construction and renovation projects.
  https://beopt.nrel.gov/home
- Building Design Advisor: Provides energy modeling in a CAD-like environment, simulating energy and daylighting performance from imported drawing files.
  http://gaia.lbl.gov/BDA/
- DesignBuilder: Software that allows quick modeling and comparison of designs relative to whole-building energy simulation. It provides visualization through 3-D modeling, including calculations of heating and cooling loads with an OpenGL EnergyPlus interface. Areas of focus include: carbon dioxide emissions, solar shading, natural ventilation, daylighting, comfort studies, CFD, HVAC simulation, pre-design, early-stage design, building energy code compliance checking, building stock modeling, hourly weather data, and heating and cooling equipment sizing.
  http://www.designbuilder.co.uk
- EnergyPlus: This program aims to combine the best features of BLAST and DOE-2, in order to provide a detailed HVAC system performance analysis that includes passive energy sources and strategies. Considerable user training is required.
  http://apps1.eere.energy.gov/buildings/energyplus/
- Energy Scheming: Using schematic drawings generated on screen (Mac), this program calculates thermal performance for four months (representing the four seasons), with passive strategies included. Design advice accompanies the performance information.
  Prof. G. Z. Brown, Energy Studies in Buildings Laboratory, Department of Architecture, University of Oregon, Eugene, OR 97403-1206
- EnvStd: Determines compliance with the envelope trade-off aspects of ANSI/ASHRAE/IESNA 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. The software is updated as the standard is updated.
  ASHRAE, 1791 Tullie Circle NE, Atlanta, GA 30329
- eQUEST (QUick Energy Simulation Tool): This tool is primarily a spreadsheet-based energy analysis program for use at all phases of design. Simulation results are achieved by creating the building model, applying energy efficiency measures, and analysis using the latest version of the DOE-2 building energy use simulation program.
  www.doe2.com/equest/
- HEED (Home Energy Efficient Design): This software program allows the user to analyze the variables of energy, cost, and carbon emissions. There are simplified and detailed input options, fit for both beginners and advanced-level users.
  http://www.energy-design-tools.aud.ucla.edu/heed/
- Opaque: Graphically displays the thermal performance of a wall or roof of any composition, any color, any orientation, and at any latitude.
  http://www.energy-design-tools.aud.ucla.edu/

(d) Environmental Assessment

- Athena: Allows a user to analyze the potential environmental impacts of a project in order to engage in informed decision making.
  http://www.athenasmi.ca/
- BREEAM (Building Research Establishment Environmental Assessment Method): This well-tested UK program, in use since 1990, rates designs and building management policies, awarding certificates of overall performance (pass, good, very good, or excellent). Priority areas can be targeted early in design, making this potentially useful as a design tool.
  Building Research Establishment, Marston, Watford, WD2 7JR, United Kingdom
- Green Building Assessment Tool (GBTool): Developed for use in the ongoing Green Building Challenge (now Sustainable Building Challenge), this analysis tool has been developed at various levels of detail and includes a weighting system with defaults that can be modified to reflect regional priorities. The "narrative" that accompanies the tool makes for an interesting comparison with the U.S. Green Building Council LEED program.
  International Initiative for a Sustainable Built Environment:
  http://www.iisbe.org/iisbe/gbc2k5/gbc2k5-start.htm/

(e) Solar Energy Analysis

- F-Chart: These programs (a suite) allow analysis of various collector and system types (including some passive heating strategies).
  http://www.fchart.com/fchart/
- PVWatts: Computes the predicted performance of photovoltaic systems, along with the associated cost savings. It comes in two versions—*Site Specific Data Calculator* (the user selects from a list of available sites) and *Grid Data Calculator* (any U.S. location may be specified). This is a really nice analysis tool and is highly recommended as: (1) a handy design tool and (2) an indication of what a useful design tool looks like.
  http://www.nrel.gov/rredc/pvwatts/

Note the woefully short listing of solar analysis software available to the building designer. Analysis capabilities for passive solar heating systems and passive cooling systems are embedded in many whole building energy analysis programs—but extracting and focusing on the passive design aspects is often a difficult chore. This is one reason for the emphasis in this book on hand-calculation methods for preliminary design.

(f) Fire Safety

- Fire-Safe Building Design for Architects and Designers: A self-paced, interactive CD-ROM that combines graphics, text, narration, animation, and video. It allows the user to manipulate graphics, make materials selections, consult supporting fire safety tables, review videos, and explore a library of static and animated appendices. Feedback is provided, encouraging improvements to fire safety during design.
  National Fire Academy, USFA/FEMA, 16825 South Seton Ave., Emmitsburg, MD 21727

(g) Daylighting and Electric Lighting

- AGI32: Performs point-by-point calculations of direct or reflected light on any real surface or imaginary plane. It can be used to predict/quantify the distribution of electric light or daylight. Raytracing, daylight factor, and glare rating calculations are included.
  Lighting Analysts, Inc.: *http://www.agi32.com/*
- Autodesk 3ds Max Design: Includes 3D modeling, rendering, animation, specialized visualization (including lighting effects from indirect illumination and shadows under varying conditions of daylight and electric light), as well as expanded imagery and cinematographic effects. The scope of this product goes well beyond building design.
  Autodesk: *http://usa.autodesk.com*
- Desktop Radiance: A software package that integrates the Radiance Synthetic Imaging System with AutoCAD Release 14 for lighting modeling. Includes libraries of materials, glazings, luminaires, and furnishings.
  Lawrence Berkeley National Laboratory: *http://radsite.lbl.gov/deskrad/*
- Form•Z RenderZone Plus: A full modeling and drafting program with photorealistic rendering based on the LightWorks® rendering engine.

It offers the following rendering levels: simple, z-buffer, and raytrace. At the simplest level, the designer can begin with a 3D model and gradually turn on features to render at the most photorealistic level. Form•Z RenderZone Plus includes "global illumination" techniques and displays accurate distribution of light in the environment.

AutoDesSys, Inc.: *http://ftp.formz.com/products/renderzone/renderzone.html*

- Visual: This software includes several lighting calculation tools and three-dimensional modeling capabilities intended to provide comprehensive analysis for lighting design projects.

  Lithonia Lighting: *http://www.visual-3d.com*

(h) Life-Cycle Costing

- Building Life-Cycle Cost Program (BLCC): Developed by the National Institute of Standards and Technology (NIST) for the Federal Energy Management Program (FEMP). BLCC provides a computer-based structure for life-cycle cost analyses in conformance with *Handbook 135 (Life-Cycle Costing Manual for the Federal Energy Management Program)*.

  http://www.eere.energy.gov/femp/information/download_blcc.html

(i) Multipurpose Suites

- Autodesk Vasari: An energy performance analysis program with heating/cooling, airflow, and carbon analysis plug-ins, among others. It is fully compatible with Autodesk Revit.

  http://autodeskvasari.com/
- Ecotect: A building analysis software program offering a range of modeling and analysis features such as visualization, shading, shadows, solar analysis, lighting, thermal performance, ventilation, and acoustics. It can export to Radiance for high-level raytracing techniques. Daylighting capabilities can model shadows and reflections on the surfaces of other buildings at a single point in time, show an entire year's shadow patterns for a single surface, model surface solar radiation relative to the effects on thermal mass, and calculate daylight factor. It is hard to tell whether this once-innovative suite of analysis tools is currently being actively supported.

  http://usa.autodesk.com/ecotect-analysis/

Index

A

D

F

M

U

WILEY END USER LICENSE AGREEMENT